VOLUME XXVI NUMBER 1

THE

JOURNAL OF GEOLOGY

JANUARY-FEBRUARY 1918

JUN 27 1919

LOW-ANGLE FAULTING

R. T. CHAMBERLIN AND W. Z. MILLER
University of Chicago

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INTRODUCTION

In the literature of structural geology it is commonly stated that rigid materials subjected to non-rotational strain tend to fracture along planes which are inclined approximately 45° to the direction of applied force. This conclusion has been developed partly from a mathematical analysis of stress and strain relations and partly from results observed in the familiar practice of crushing cubes of building stone to determine their strength. That 45° is the angle at which rigid materials normally fracture under direct compressive stress appears to be very generally accepted. This angle, therefore, has come to be regarded by structural geologists as the theoretical angle at which thrust faulting, under ordinary conditions, should occur.

But if the actual angles of dip of a large number of thrust-fault planes in the earth be tabulated and averaged, it is found that the mean inclination is less than 45° from the horizontal. According to Leith an average compiled from folios of the United States Geological Survey gives a dip of 36° for planes of thrust faults and 78° for planes of normal faults.[1] An inspection of numerous cross-sections from various other countries gives results in fair agreement with these figures. The average dip angle of thrust-fault planes, as they occur in nature, is considerably less than 45°.

While the most prevalent type of thrust-fault plane, that of the ordinary reverse fault, dips somewhat less steeply than 45°, it still does not depart widely from that governing angle. Nevertheless, in notable variation from this, field studies in the last few years have brought to the attention of geologists impressive evidence of the prevalence and the great importance of what may well be called a different genus of fault, namely, the great low-angle overthrust. Its generic characteristics are the very low inclination of its fault plane and the extraordinary horizontal displacement often attained. Such low-angle overthrust faulting has been well described, as it is strikingly shown in the Northwest Highlands of Scotland, where the Moine, Ben More, Glencoul, and other remarkable thrusts form

[1] C. K. Leith, *Structural Geology*, 1913, p. 55.

classic examples of the genus (Fig. 1).[1] In the extreme north of Sutherland the various rock groups overlying the Moine thrust plane can be shown to have been driven westward for a distance of ten miles.[2] Horizontal shiftings of comparable magnitude occurred along the Ben More, Glencoul, and other planes of thrusting which lie beneath the Moine thrust and add to the remarkable nature of the phenomena. Though since thrown into gentle folds, in many places it is clear that these planes of slippage were originally not far from the horizontal. In some other portions of the British Isles analogous phenomena have been observed.

Similarly, in Scandinavia the very intense Caledonian deformation manifested itself in horizontal overthrusting of astonishing magnitude. The vertical displacement is slight, but the horizontal slip is measured in tens of kilometers.[3]

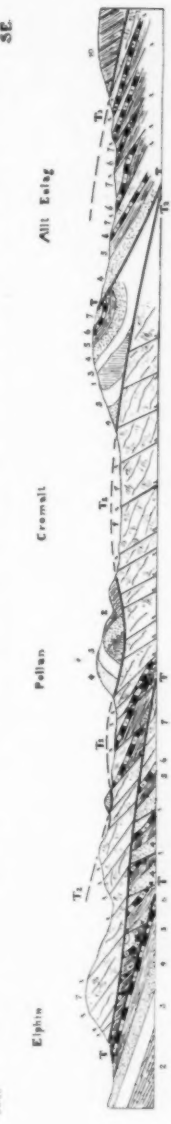

FIG. 1.—The Scottish Highland type of overthrust. Section from Elphin to Allt Ealag (about 6 miles in length). The thrust plane (T_3) near Allt Ealag on the right is the Moine overthrust. The gently folded thrust plane (T_2) which runs nearly the whole length of the section is that of the Ben More thrust. Two other major thrusts cut through the faulted slices near the left end of the section. Note the relation of the overthrusts, or major faults, to the minor reverse faults. From "Report on the Recent Work of the Geological Survey in the North-West Highlands of Scotland, Based on the Field-Notes and Maps of Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman and H. M. Cadell," *Quart. Jour. Geol. Soc.*, XLIV (1888), 426, Fig. 19.

[1] B. N. Peach, John Horne, W. Gunn, C. T. Clough, and L. W. Hinxman, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 463–594.

[2] John Horne, *ibid.*, p. 469.

[3] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Bergbyggnad. Kongl," *Svenska Vet. Akad. Handl.*, Bd. 28, No. 5 (1896), pp. 190–95 and Pl. IV; P. J. Holmquist, "Bidrag till diskussionen om den skandinaviska fjällkedjans tektonik," *Geol. Fören. Förhandl*, XXIII (1901), 55–71.

In the southern Appalachian Mountains the Rome and Cartersville overthrusts run parallel to each other for over 200 miles. They are thought by Hayes to show horizontal displacements of not less than 4 miles and 11 miles respectively, and possibly much more. The inclination of the fault planes is here frequently as low as 5°; it is rarely more than 25°.[1] The steeper portions of the plane as now seen are largely the result of subsequent warping. Farther north, in Tennessee, a possible continuation of the Cartersville thrust is the Buffalo Mountain fault which, according to Keith, was a low-angle overthrust whose original displacement along the shear plane was at least 20 miles.[2] Subsequent folding and faulting have so disturbed this fault plane that its original inclination cannot be very closely determined.

More to the north, the earlier Taconic revolution also developed low-angle overthrusts. Of these may be noted the Great Western fault of eastern New York,[3] the St. Lawrence and Champlain fault, which runs from Vermont to the city of Quebec and beyond,[4] and possibly the Cowansville overthrust of Missisquoi and Brome counties, Quebec, though the age of the last has not been closely determined as yet. In any case the measured horizontal displacement of the last is 11 miles, and it is thought likely that the actual displacement was much greater.[5] It is a nearly horizontal overthrust, whose plane is very close to the present surface, and along which the Georgian slates on the east have been shoved over the Trenton slates and limestones of the Farnham series to the west.

The Rocky Mountains of Montana and Alberta are bordered on their eastern front, throughout at least 350 miles of their extent,

[1] C. W. Hayes, "The Overthrust Faults of the Southern Appalachians," *Bull. Geol. Soc. Amer.*, II (1891), 141–54.

[2] Arthur Keith, *U.S. Geol. Surv. Geol. Atlas, Roan Mountain (Tenn.)*, Folio 151, 1907, p. 9.

[3] James D. Dana, *Manual of Geology* (4th ed.), 1895, p. 528; S. W. Ford, "Observations upon the Great Fault in the Vicinity of Schodack Landing, Rensellaer County, N.Y.," *Am. Jour. Sci.*, XXIX (1885), 16–19.

[4] G. A. Young, "The Geology and Petrography of Mount Yamaska, Province of Quebec," *Geol. Surv. Can. Ann. Rept.*, XVI (1906), 9.

[5] Robert Harvie, "Brome and Missisquoi Counties, Quebec," *Sum. Rept., Geol. Surv. Can.*, 1914, pp. 98–99.

by great overthrusts whose planes dip in under the mountains at low angles. McConnell has estimated that on the South Fork of the Short River in Alberta the horizontal displacement of the Cambrian strata—which here rest upon the Cretaceous—has been about 7 miles, while the vertical displacement amounts approximately to 15,000 feet.[1]

In the Glacier National Park of Montana, Willis found the Proterozoic strata which make up the outermost range (here called the Lewis Range) overthrust at least 7 miles upon the Cretaceous of the foothills. The dip of the thrust plane, as determined by Willis by graphic construction, ranges from 3° to 7° 45′.[2] More recently Campbell has been able to show that where the Great Northern Railroad crosses the range this great mass of strata has been shoved at least 15 miles northeastward along the Lewis thrust plane, and were the original position of the mountain mass known the distance might prove to be much greater.[3]

At the International Boundary the northward continuation of the Lewis thrust has been termed the Waterton Lake thrust by Daly. The known extent of the bodily movement here represented is about 8 miles, as measured on the perpendicular to the line tangent to Chief Mountain and the outermost mountains of the Clarke Range. But the actual movement, according to Daly, has probably been 10 miles or more, and may be as much as 40 miles, for "it is not impossible that the entire Clarke Range (the equivalent of the Livingston Range of Willis) in this region represents a gigantic block loosened from its ancient foundations, like the Mount Wilson or Chief Mountain massifs, and bodily forced over the Cretaceous or Carboniferous formations."[4]

The Willard thrust discovered by Blackwelder in the Wasatch Mountains of Utah has a displacement, so far as exposed, of about 4 miles, though this is probably but a small fraction of its total

[1] R. G. McConnell, *Geol. Surv. Can.*, II (1886), Part D, p. 33.

[2] Bailey Willis, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

[3] M. R. Campbell, "The Glacier National Park," *Bull. 600, U.S. Geol. Surv.*, 1914, p. 12.

[4] R. A. Daly, "Geology of the North American Cordillera at the Forty-Ninth Parallel," *Mem. 38, Geol. Surv. Can.*, Part I (1912), p. 91.

displacement. Though the fault plane locally has a dip as high as 50° owing to later warping, it averages about 15°.[1]

The Bannock overthrust, recently described by Richards and Mansfield, when traced through southeastern Idaho and Utah along its course, now made sinuous by erosion, has a length of approximately 270 miles, and involves a horizontal displacement of not less than 12 miles.[2] The thrust plane itself is a gently undulating surface nowhere steeply inclined, sometimes dipping to the east and sometimes to the west. If this slight plication be the result of subsequent folding, the shear plane must originally have been very nearly horizontal.

In eastern Wyoming the Absaroka and Darby faults are really of the overthrust variety, although what remains of these planes shows a higher angle of inclination than most of the preceding.[3] The fault plane of the Darby thrust is, in general, not far from parallel to the bedding of the overthrust sheet. East of Yellowstone National Park the Hart Mountain overthrust is thought by Dake to show a displacement of not less than 22 miles, making no allowance for recession of the eastern front by erosion.[4] Assuming average thickness for the beds involved, the vertical displacement is over 6,000 feet.

In the Alps, so long and carefully studied, some of the most remarkable structures known to geologists are still in process of being worked out. As yet there is lack of perfect accord as to some of the features of their interpretation. They have commonly been interpreted as extraordinary and wonderfully drawn-out overfolds (*nappes de recouvrement*). Among certain geologists there has developed a disposition to substitute, in interpretation, overthrust sheets of the Scottish Highland type[5] for these extreme

[1] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 517–42.

[2] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust, a Major Fault in Southeastern Idaho and Northeastern Utah," *Jour. Geol.*, XX (1912), 681–709.

[3] Alfred R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *Bull. 543, U.S. Geol. Surv.*, 1914, pp. 84–87, and structure sections.

[4] C. L. Dake, "The Hart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, XXVI, No. 1 (1918), p. 50.

[5] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithsonian Misc. Coll.*, LVI (1912), No. 31, pp. 1–13; also James Geikie, *Mountains, Their Origin, Growth, and Decay*, 1913, pp. 116–17.

overfolds. If this be the true explanation, it would add to our list this remarkable structure of the Alps as a most pronounced and complicated case of low-angle faulting.

Similar structures have been reported from Spain, Euboea, the Balkans, and the island of Timor; in the last case an extensive sheet of shallow water strata, ranging in age from Triassic to Eocene, has been thrust over what appear to be deep-sea deposits of nearly the same age.[1]

Detailed studies elsewhere—practically the world over, indeed—are bringing to light overthrust faults of great displacement along gently inclined planes. This sort of faulting seems, therefore, to constitute a phenomenon of a definite, independent type. It seems to belong to a genus of its own, distinct from the ordinary reverse fault, though the two are no doubt connected by composite types that bind them together. The common reverse fault is defined by displacement along planes neighboring 45° or a little less, and is confined to more limited movement on these planes, while the great overthrusts slide along planes that approach horizontality and involve displacements of astonishing magnitude. Though each great low-angle overthrust is commonly attended by a retinue of reverse faults of lesser magnitude—a fact which suggests that there may be a kinship between them—nevertheless an inspection of any good section, as in the Scottish Highlands, shows a radical difference between the two types. Some distinctive feature seems to be added to simple straight compression to form the low-angle overthrusts.

PREVIOUS INVESTIGATIONS

Willis has divided thrust faults into four classes, the break-thrust, stretch-thrust, shear-thrust, and erosion-thrust. Of these the shear-thrust and the erosion-thrust are low-angled overthrusts, while the other two classes belong to the more common group of reverse faults. The shear-thrust is a class to cover the conspicuous Scottish Highland type, while the erosion-thrust covers a special case of alternate competent and incompetent strata in which the upper competent formation carrying the thrust is first removed

[1] G. A. F. Molengraaff, "Folded Mountain Chains, Overthrust Sheets, and Block Faulted Mountains in the East Indian Archipelago," *Compte Rendu, Congrès Géol. Int.* (Toronto, 1913), pp. 689–702.

from the crest of a broad anticline by erosion. When subjected to further lateral thrust, the upper beds on one limb of this anticline, encountering little resistance in front, ride forward over the subaërial surface.[1] Related to this form of erosion-thrust is another special type described by Hayes from the southern Appalachians.

Thus the field of the low-angle fault is not an unexplored one, since explanations have been offered for certain special types of overthrusts. The very definite explanation for the Rome and Cartersville overthrusts of the Southern Appalachians was worked out by Hayes as early as 1891.[2] The key of this explanation was suggested by the massive and peculiarly competent dolomite formations which alternate with weaker shale layers. In this

FIG. 2.—A theoretical section to represent the position of the fault plane (*PP'*) in the Rome and Cartersville thrusts. From Hayes.

type of deformation the strata are thought to have first flexed into a pair of gentle anticlinal bends some notable distance apart. Between the flexures the strata remained essentially undisturbed. Finally a break occurred near the crest of one of the anticlines, and the thick, competent formations sheared more or less horizontally along a slippage plane which followed closely the bedding of the weak shales (Fig. 2).

The erosion-thrusts of Willis and the special form so clearly described by Hayes are dependent upon appropriate rock strata and structure, and thus these explanations, while they fit admirably the conditions in the southern Appalachians for which they were devised, do not apply to various other overthrusts where the necessary stratigraphic conditions do not obtain. They thus constitute a particular type due to special conditions. They do not apply to the very remarkable overthrusts of the Scottish High-

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), pp. 222–23.

[2] C. W. Hayes, *loc. cit.*, II (1891), 141–54.

lands, where the thrust planes cut through very heterogeneous assemblages of rock material. Different principles apparently control the latter.

It was with a view to obtaining light upon the mechanism of the Scotch overthrusts that Cadell, in 1888, even earlier than Hayes, undertook his experimental researches which since have become classic. In these instructive researches Cadell made use of a pressure box, one side of which could be thrust forward by means of a powerful screw. In this box he built up a succession of layers of plaster of Paris, interstratified with layers of sand, to imitate beds in the earth. After the plaster had set into rigid strata, lateral pressure was applied by means of the screw which moved the pressure block. In this manner, as the final outcome of many trials, he succeeded in imitating rather closely the peculiar imbricate and overthrust structure which the members of the Scottish survey were deciphering from the greatly disturbed terranes of the Northwest Highlands.[1]

Those of Cadell's conclusions which relate to overthrusting may be quoted:

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

2. The compressed mass tends to find relief along a series of gently inclined thrust planes, which dip toward the side from which pressure is exerted.

3. After a certain amount of heaping up along a series of minor thrust planes, the heaped-up mass tends to rise and ride forward bodily along major thrust planes.

4. Thrust planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

5. A thrust plane below may pass into an anticline above, and never reach the surface.

6. A major thrust plane above may, and probably always does, originate in a fold below.

7. A thrust plane may branch into smaller thrust planes, or pass into an overfold along the strike.

8. The front portion of a mass of rock being pushed along a thrust plane tends to bow forward and roll under the back portion.

9. The more rigid the rock the better will the phenomena of thrusting be exhibited.

[1] H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXXV (1890), 337–57.

The result of Cadell's experimentation was to produce a concrete picture of the manner in which the complex structure of the Northwest Highlands may have developed. As pressure was gradually applied, the artificially prepared strata were first sliced into separate blocks by ordinary reverse slice faults which dipped in the direction from which the pressure was applied. A piling up of the sliced blocks followed. After sufficient piling up had occurred, a low-angle major thrust plane broke through the piled-up mass of slices, and the whole overlying mass rode forward bodily upon this gently inclined plane which Cadell termed the "sole" (Fig. 3). This behavior would seem to suggest that the heaping up of material

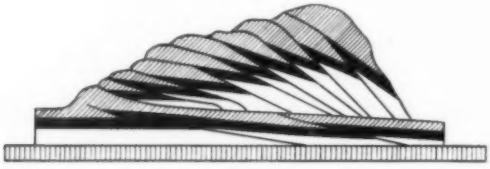

FIG. 3.—Major thrust plane, or "sole," cutting across minor slice faults. After Cadell.

is an important factor in determining the subsequent break along the low-angled "sole."

A pressure box patterned somewhat after that of Cadell was employed by Willis in his experiments upon Appalachian structure.[1] But in these interesting and well-known experimental researches folding rather than faulting was the prime object of the investigation. To obtain the desired results Willis used somewhat softer materials than those employed by Cadell, and heavily weighted the strata with a thick covering of shot to prevent too ready yielding. The hardest layers, in most cases, were composed of equal parts of plaster and wax, while the less competent beds were still further softened by the addition of turpentine, and often by leaving out plaster altogether. Fracturing occurred only very incidentally.

Further researches by Paulcke were directed toward reproducing experimentally the folds of the Jura, and the marvelous overfolded

[1] Bailey Willis, *U. S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), Pl. LXVI, opposite p. 258.

and overthrust structure of the Alps.[1] With this end in view Paulcke adopted a stratigraphic series which, in most cases, comprised a thick basal layer of sand, above which were eight or nine alternating layers of clay and plaster. The mass was then weighted above by a very thick covering of sand. Because of the nature of the materials, fracturing of quite variable sorts developed—both typical reverse faults and a few low-angle overthrusts in which a strong plaster bed carrying the thrust was shoved bodily over the less competent clayey material beneath. But the brittle layers of plaster broke into numerous small rectangular blocks in addition to the major folding and faulting, and these small blocks were so rotated, shattered, and irregularly displaced as to mask much of the more significant behavior of the strata under compression. In general outlines, however, various cross-sections of the Alps were reproduced.

The experiments of Cadell suggested that the piling up of weight may be an important factor in determining the low-angle overthrusts, and that perhaps the question may be solved by experimentation. This stimulated us to attempt further experimentation in an effort to determine the influence of various contributing factors upon the angle of faulting.

METHODS OF PRESENT EXPERIMENTAL INVESTIGATION

Apparatus.—For these studies a pressure box was constructed along lines similar to those adopted by Cadell and Willis (see Fig. 4). This box differed, however, from the previous ones in having screws and movable pressure blocks at both ends, instead of solely at one end. Pressures could thus be applied from opposite directions whenever desired. But it was found, early in the progress of the work, that these pressure blocks frequently manifested a strong tendency to rise up from the floor of the box and to become tilted as the faulting of the strata progressed. To prevent this, long steel guide flanges were bolted on the inner sides of the box at a height of about an eighth of an inch above the top of the pressure block. With this control the pressure block could only move forward and backward, and the tilting of the block was thus practically

[1] W. Paulcke, *Das Experiment in der Geologie* (Berlin, 1912), pp. 74–108.

eliminated. One side of the box was constructed so that it could be removed as often as desired during the course of each experiment in order to note the nature and progress of the deformation and to photograph the structure developed. Pressures were applied by means of a $1\frac{1}{4}$-inch steel screw turned by hand, operating upon a lever arm of 24 inches. At the opposite end of the box the other pressure block was moved by a 1-inch screw. This was much less frequently used. These screws were capable of developing such thrusts that one of the chief difficulties was to secure an apparatus of sufficient strength to withstand the stresses to which it was

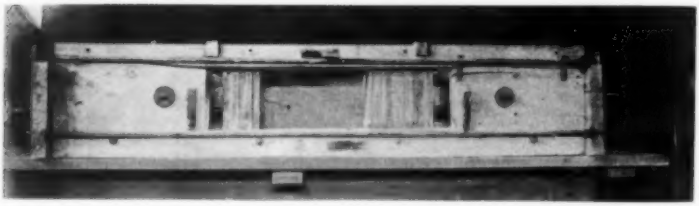

FIG. 4.—Pressure box with a movable thrusting block at each end. The detachable side has been removed to permit a view of the interior.

subjected. Various strengthening devices were employed. If another apparatus were attempted, it would be constructed entirely of steel.

Materials.—Before attempting experiments upon a succession of strata of varying competency, as would be the case in nature, it was essential to determine the effect of compressive stresses on homogeneous material. Both rigid and plastic materials were compressed in the crushing machine to determine their different behavior under stress. For rigid material either plaster of Paris or a mixture of plaster with a small amount of clay was used. As a result of many trials it was found that to secure rigid, brittle material, such as best illustrates faulting, a mixture of three parts of plaster and one part of clay gave the best results. To develop greater plasticity the proportion of clay was steadily increased, and in various cases a certain proportion of sand was added until there was as much as two parts of clay and sand to one part of plaster.

In preparing this combination it seemed best to mix the plaster and clay dry and, when thoroughly mixed, to put the mixture in the machine in that state and wet it down with water as the material was poured in. The most homogeneous mixtures were developed in this manner.

When the box was filled to the desired depth, the wet mass was allowed to set for a period of from three to seven days, until the material was not readily dented with a trowel. The length of time required depended considerably upon the combination of materials used. The greater the proportion of clay the longer the period of time necessary for the material to harden. When deemed sufficiently hard, the screw was turned and the process of crushing begun. The pressure was brought to bear gradually. After a single turn of the screw, or only a small fraction of a turn, the side of the box was removed and the resulting deformation observed. This cautious turning of the screw, with frequent halts to view the results, was maintained till the end of each experiment.

After treating structureless homogeneous materials of a considerable range of competency, tests were made with bedded homogeneous materials to discover how simple bedding planes, as lines of weakness, influenced the angle of faulting. The procedure was to place a layer of equal parts of plaster and clay in the machine, soak it thoroughly with water, and quickly smooth it with a trowel. After a few minutes, when the bed had hardened slightly, another layer of the same material was laid upon it and treated in the same manner. In this way five or six layers were built up. The whole mass was then allowed to set until rigid, and afterward crushed.

To test the influence of an alternation of beds of different competency upon the angle of faulting, Cadell's line of attack was followed at the outset. Plaster and sand were used respectively for the competent and incompetent beds. The sand was poured into the machine, bedded down, and then well dampened with water. While still wet a layer of pure plaster was added, followed as quickly as possible by another layer of sand and another of plaster, until four to six layers were built up. The plaster absorbed water at once and became hard, so that a long wait before crushing was less necessary than when clay was involved.

Troublesome difficulties arose from the use of these materials. Owing to the incoherence of the sand, the competent plaster layers, instead of rising along a single fault plane after fracturing had occurred, were thrust into the sand layers, producing a dovetail effect. Obviously it was necessary to add something to the sand to correct this and to give the sand more coherence, and yet at the same time the sand layers were to be kept relatively incompetent. With this end in view varying amounts of plaster were added to the sand and the result noted. But it was found that if sufficient plaster were added to furnish the desirable coherency, the layer became too competent for the purpose of the experiment. Clay alone was tried, but owing to the weakness of the clay, or its lack of adhesion to the plaster, dovetailing again resulted. To obviate this, plaster was added to the clay in the proportion of about two parts of clay, with some sand, to one part of plaster. This combination was successful, though in different experiments, where varying degrees of competency were desired, somewhat different proportions were used. As would be expected, the plaster layers carried the thrust, and the whole mass acted as a rigid body until these competent layers were fractured. The influence of softer layers after fracturing will be discussed later.

In certain experiments it was desired to give the competent layers somewhat greater plasticity. This necessitated increasing the plasticity of the incompetent layers as well, in order to keep the relative competency the same. For this series of experiments a mixture of plaster, clay, and sand was used for the competent beds, varying in proportion from three parts of plaster and one of clay and sand to two parts of plaster and one of combined clay and sand. For the incompetent beds either pure clay was used, or a mixture of clay and plaster varying in proportion from four of clay and one of plaster to two of clay and one of plaster. Such strata required from three to seven days to harden, depending upon the proportions of clay and plaster used.

RELATION OF FAULTS TO STRESS AND STRAIN

Stresses may be defined as the forces developed within different parts of a structure under the action of external forces operat-

ing upon it, and strain as the change in the shape or dimensions of the body resulting from stress. Strains may be dilatational, in which there is change of volume without change of form, or distortional, in which the form of the body is changed without changing the volume. Of these the latter is by far the more important in the deformation of rocks. Distortional strains may result from three kinds of stress—tensile, compressive, and shearing stress—torsion being regarded as shearing by twisting. Various combinations of these stresses are of frequent occurrence.

In the problem of thrust faulting under consideration, the deformation results from the action of compressive stresses and shearing stresses, with tension only a very subordinate and incidental factor. The operation of these stresses may be analyzed as follows:[1]

Consider a rectangular block with pressure P applied uniformly to a face to find the stress on the oblique section *mnop*.

Resolve P into normal (N) and tangential (T) components. If the angle between the direction of application of force (P) and the plane of the oblique section (*mnop*) be designated θ, then

$$N = P \sin \theta$$
$$T = P \cos \theta$$

The tangential component T tends to cause sliding along the section *mnop* and is called the shearing stress. The normal component N is called the normal or direct stress.

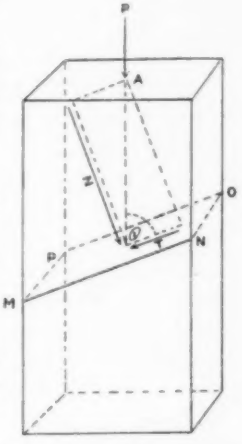

FIG. 5.—Diagram to represent the normal or direct stress (N) and the tangential or shearing stress (T) operating on an oblique section (*mnop*). The force (P) is applied uniformly on face A.

Let a represent the area of the cross-section of the block, or column, upon which the force is applied. Then the area of the oblique section *mnop* equals $a \csc \theta$.

[1] W. C. Unwin, *The Testing of Materials of Construction*, 1910, pp. 22–23; R. J. Woods, *The Theory of Structures*, London, 1909, pp. 1–4.

Hence the stress per unit area, or the intensity of stress, on section *mnop* is seen to be:

(1) $$\text{Normal stress } (Pn) = \frac{P \sin\theta}{a \csc\theta} = P \sin^2\theta.$$

(2) $$\text{Tangential stress } (Pt) = \frac{P \cos\theta}{a \csc\theta} = P \sin\theta \cos\theta.$$

For an oblique section at right angles to *mnop* substitute $90° - \theta$ for θ and get

$$P'n = P \cos^2\theta.$$
$$P't = P \cos\theta \sin\theta = Pt.$$

Thus the intensity of tangential stress is the same on two oblique sections at right angles to each other.

The value of $P \sin\theta \cos\theta$ reaches a maximum for $\theta = 45°$ when it equals $\frac{1}{2}P$. The intensity of the shearing stress is therefore greatest for planes at 45° to the line of propagation of the force.

Since the intensity of the shearing stress is as a maximum when $\theta = 45°$, it was natural enough to suppose that fracturing under compressive stress should occur normally along planes inclined 45° to the line of application of the force, and in the familiar practice of crushing cubes of stone, cement, wood, etc., in testing machines to determine their strength for building purposes, experience is that the blocks break at angles approaching 45°, though most frequently the angle is somewhat less than this. Forty-five degrees is the angle which is commonly stated to be the angle of fracture in the geologic literature which deals with faulting and jointing under compressive stresses.

But, as has been noted, many thrust-fault planes are found to dip at angles much less than 45°, and short blocks in the crushing machine very commonly break at angles as low as 30°. Fracturing at 30° in our experiments has been commoner than at the higher angle of 45°. What is the meaning of this? Experimental error fails to satisfy the discrepancy, as an error of 15° is unlikely and the persistence of 30° and 35° breaks shows that there is some important factor, or factors, in operation which have not been considered. Let us therefore consider some of the possible factors which may operate to reduce the angle of fracture from the theoretical 45°.

FACTORS WHICH LOWER ANGLE OF FAULTING

A. EFFECT OF NORMAL COMPONENT OF STRESS

While the tangential or shearing stress ($Pt = P \sin \theta \cos \theta$) reaches its greatest intensity along planes inclined 45° to the line of application of the force P, it is also true, as has just been shown, that the intensity of the stress at right angles to this ($Pn = P \sin^2 \theta$) is likewise great. This normal stress obviously acts as a frictional resistance to shearing by the tangential stress. The value of this frictional resistance depends on the shearing strength of the material when not in compression.[1] As to the potency of this factor, Church states that the presence of compressive stress normal to the 45° plane is sufficient to strengthen the material for shearing in that plane, causing separation to occur along a plane where the compressive stress is considerably less.[2]

Let us see how this plane will be inclined. The intensity of the normal stress is expressed by

$$Pn = P \sin^2 \theta.$$

Its intensity increases as θ increases, and diminishes as θ decreases (see Fig. 6). Hence the lower the angle of the fracture plane, the less will be the frictional resistance due to normal compressive stress.

The intensity of tangential or shearing stress ($Pt = P \sin \theta \cos \theta$) is greatest when $\theta = 45°$, and diminishes as θ becomes less. Shearing can occur only when this exceeds the shearing strength of the material. Here is a limiting factor.

Comparing

$$Pn = P \sin^2 \theta$$

and

$$Pt = P \sin \theta \cos \theta,$$

it is seen that as θ becomes less $P \sin^2 \theta$ diminishes in value more rapidly than $P \sin \theta \cos \theta$ or, in other words, as the angle θ is lowered from 45°, the intensity of normal stress is reduced more rapidly than the intensity of the tangential stress. Therefore,

[1] W. C. Unwin, *op. cit.*, p. 419.

[2] I. P. Church, *Mechanics of Engineering* (New York, 1913), p. 220.

since the resistance due to the normal stress is reduced more rapidly than the intensity of tangential stress, as the angle is lowered from 45°, fracturing so far as determined solely by these two factors is made easier with the reduction of angle. But on the other hand, the intensity of tangential stress must exceed the shearing strength of the material in order to produce fracturing, and since this intensity diminishes with a lowering of the angle from 45° downward, the angle must not be too low to allow the

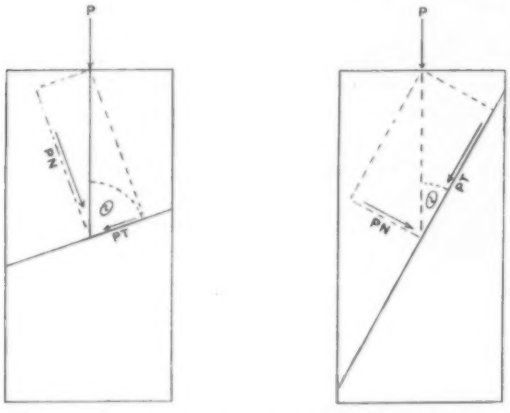

FIG. 6.—Diagrams to show how the relative intensity of the normal (*Pn*) and tangential (*Pt*) stresses on an oblique section is a function of the inclination of the section to the direction of application of the force. In the left-hand figure the direct stress exceeds the tangential in intensity; in the right-hand figure, with a lessening of the angle between the direction of the force and the plane of the section, the tangential stress is the more intense.

requisite intensity. This is the limiting factor which prevents breaking at too low an angle. The breaking plane is thus determined by a balance of these three factors. This helps to explain why homogeneous material, when subjected to compression, so persistently fractures at angles lower than 45°, although the shearing stresses reach their greatest intensity in the 45° planes.[1]

[1] A mathematical analysis leads to the conclusion that the inclination of the surface along which there is the greatest tendency to rupture is lowered from 45° by $\frac{\phi}{2}$, where ϕ is the angle of friction, or angle of repose, of the grains of the material. For

But as the favorite angles of fracturing for these blocks of homogeneous material appear to be 30°, or 35°, or 40°, the effect of frictional resistance due to the component of stress normal to the fracture plane clearly is not an adequate explanation of the great, low-angled overthrusts whose planes of fracture are commonly inclined at only 5° or 10° from the horizontal. There must be other factors.

B. EFFECT OF HETEROGENEITY OF MATERIAL

It is to be recognized that the angle of faulting is to some extent dependent upon the uniformity or heterogeneity of the material. Tests on the strength of materials seem to show that most blocks fail by a combination of shear and splitting. Only short blocks of very uniform texture will fail by shear entirely across the section in one plane.[1] Heterogeneous material which introduces differences in composition introduces irregularities in fracturing, and these irregularities are prevailingly in the nature of a lowering of the angle of fracture. But this alone will hardly explain the great overthrusts.

C. POSSIBLE INFLUENCE OF LENGTH AND SHAPE

Length.—The short column, whose length is not more than five times its diameter, fails by direct crushing. A longer column fails partly by crushing and partly by bending.[2] Thus a distinction is made in engineering practice between the behavior of the short block and the long column. The long column first bends and then splits obliquely. That the long column should be weaker than short blocks of the same material and cross-section is evident, but the theoretical treatment of its behavior is much less satisfactory than in other cases of flexure.[3] The breaking load for long columns, however, is represented by Euler's formula:

$$P = \frac{\pi^2 EI}{l^2}$$

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cast iron the usual value of θ is about 35°, corresponding to a value for ϕ of 20° (Arthur Morley, *Strength of Materials* [London, 1913], pp. 55–56). Hodgkinson's experiments with cast iron have shown that 35° is the common angle of rupture for this material (cited by Church, *Mechanics of Engineering*, p. 220).

[1] James E. Boyd, *The Strength of Materials*, 1911, p. 48.

[2] R. J. Woods, *op. cit.*, p. 205.

[3] I. P. Church, *Mechanics of Engineering*, 1913, p. 360.

where P is the limiting load which the column can support, E is Young's modulus of elasticity, I is the least moment of inertia, and l is the length of the column.[1]

Increasing the length, therefore, weakens the resisting power of the column and increases the likelihood of fracture.

Cubes and short blocks tend tc fracture at 45°, or somewhat less. But long columns, because of the preliminary flexure, split at a lower angle. In testing the strength of cast iron in engineering practice it has been found that, as the length of the longer dimension is increased while the other two dimensions remain the same, the angle of fracture becomes lower until it reaches 30°, beyond which there is no lowering with further increase in length.[2] Experimentation upon other materials has given analogous results.

The lowering of the angle in the long column is a result of the development of rotational strain. The preliminary flexing of the column develops tensile stresses on the outer side of the bend, and at the same time develops shearing stresses by which the layers on the outer side of the bend tend to creep toward the crest of the fold. This shearing of the layers may be illustrated by bending a pack of cards. If actual fracturing occurs, the effect of the rotational couple is to lower the angle of breakage.

Earth deformation theoretically may partake of the nature either of the short block or of the long column. Except for the influence of the curvature of the surface, in most cases it would seem to parallel most closely the short block, for the dimension of the mass involved parallel to the direction of thrusting is, as a rule, less than five times the transverse dimensions of the block. The Appalachian Mountain chain is at the very least 1,800 miles in length, paralleling the Atlantic Coast. To be five times this, the northwest-southeast dimension (the length of the flexed column) would need to be 9,000 miles, or completely across North America and much of Asia. From Cincinnati to Charleston, South Carolina, on the coast, which is a most generous estimate of the distance across the deformed belt, is only approximately 900 miles. The

[1] R. J. Woods, *op. cit.*, pp. 212–13.

[2] *International Library of Technology and Mechanics* (Scranton, Pa., 1909), pp. 2–3.

vertical dimension of the vigorously deformed Appalachian block is probably less. Very likely the column need not have yielded to the deformation throughout its entire length, and so the belt actually deformed may be less than the true length of the column, but one could not safely assign to such a hypothetical column a greater length than the width of the continent. The very long Cordilleran chain would make even greater demands in this direction. Mountain ranges with their long dimension paralleling coasts from which the thrusting is assumed to have come, and with a lesser transverse dimension in the line of the thrusting, are thus to be considered as short blocks. With still less of vertical thickness involved, they are perhaps more closely analogous to the deformation of a thin prism or wall.

It is possible, however, that very locally, in a portion of a mountain range, the conditions of the long column might be operative and low-angle faulting might result, but it hardly seems likely that this principle can, in any large measure, be responsible for the great overthrusts. The most that can well be claimed for it is that it may be a contributing factor.

Shape.—The shape of cross-section of deformed masses is a factor in determining the character of the deformation which results under stress. The strength of a column depends on whether the ends are free to turn, or are fixed and thus incapable of turning. Columns with round ends bend quite differently from those with square ends.[1] The shape of a lenslike mass of sediment, weaker or stronger than the surrounding rock, may well be important in determining the nature of the deformation which takes place when the mass is stressed.[2]

D. EFFECT OF ROTATIONAL STRAIN

As designated by Hoskins[3] and applied to structural geology by Leith,[4] strains due to compression are divided into two classes—rotational and non-rotational. Non-rotational strains are defined

[1] I. P. Church, *Mechanics of Engineering*, pp. 360–61.

[2] Suggested by T. T. Quirke, personal communication.

[3] L. M. Hoskins, "Flow and Fracture of Rocks as Related to Structure," *16th Ann. Rept. U.S. Geol. Surv.*, Part I (1896), p. 860.

[4] C. K. Leith, *Structural Geology*, pp. 16–21.

as those in which the principal directions of strain remain constant with reference to the principal axes of stress throughout the deformation. Rotational strains are those in which the axes of strain are being constantly rotated with respect to the axes of stress during the deformation. The behavior of a body deformed under each of these types of strain has been admirably set forth by Leith by the use of the strain ellipsoid and the wire-netting model. As shown in Figs. 5, 6, and 7 of his *Structural Geology*, the planes of no distortion are the planes of maximum shear, and are the planes along which fracturing should tend to take place in either rotational or non-rotational strain.[1] But the inclination of these planes of shear with respect to the applied force is different in the two cases. Under non-rotational strain the shearing planes are seen to be located approximately at 45° to the direction of the applied force. Under rotational strain, on the other hand, while the relation of the shearing planes to the strain ellipsoid remains the same, the position of these planes with reference to the direction of applied force is steadily changed by rotation. In the extreme case (pure shearing) one plane of shear is seen to be parallel to the direction of the force, while the other commences at 90° to the force and is gradually lowered in angle as the deformation progresses. Fracturing is more likely to occur in the plane parallel to the force than in the one highly inclined to it.

Thus the shearing plane inclined 45° to the force in pure non-rotational strain and the corresponding shearing plane parallel to the force in extreme rotational strain may be taken as the limiting cases. It is clear that between these two limiting cases of 45° and 0° fracturing may actually take place at any intermediate angle, depending upon the relative strength of the rotational and non-rotational factors. This will perhaps be made clearer by Fig. 7.

Ellipse *A* represents the cross-section of a sphere deformed by pure non-rotational strain resulting from a uniform, horizontal compressive stress. Shearing and fracturing may occur along either of the 45° shearing planes, but more likely along plane *b* than plane *a*. In ellipse *B* the force, though still horizontally directed,

[1] C. K. Leith, *Structural Geology*, pp. 18–21.

is not uniformly distributed, but is represented as somewhat stronger at the upper end than at the lower, as indicated by the relative length of the arrows. The fracture plane (*b*) in consequence of the rotation of the ellipse is inclined at approximately 40° to the force. In ellipse *C*, with stronger rotation, the active shear plane (*b*) has been lowered to an angle of 25°. In ellipse *D*, because of still stronger rotation, the fracture plane is only 15° from the horizontal, and in *E*, the limiting case of extreme rotational strain, the shearing plane has reached horizontality.

Applying these principles to the earth, horizontal thrusts may therefore theoretically produce shearing planes at any angle from 45° down to horizontality, depending upon the relative strength of the rotational element in the strain. Actual faulting, however, would probably not take place exactly in these planes of maximum shear, but would, as shown on pages 17–19, be modified somewhat further by the component of stress acting normal to the shearing plane. A marked rotational strain derived from horizontally directed stresses, if it can be shown that such are likely to be developed with sufficient frequency in earth dynamics, may form a working hypothesis to explain the great low-angle overthrusts. It therefore becomes necessary to seek the conditions which might result in the development of such strongly rotational strains.

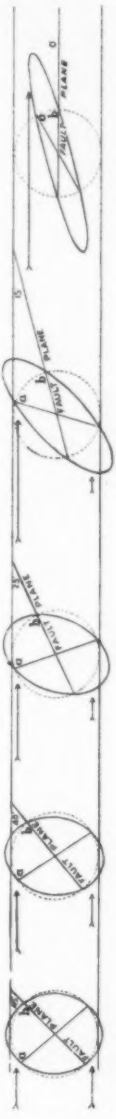


FIG. 7.—Theoretical deformation of a sphere by compressive stress. Ellipse *A*, representing the cross-section of a sphere deformed by pure non-rotational strain, is the limiting case at one end. The planes of no distortion (fracture planes) are here inclined at 45°. Ellipse *E*, representing extreme rotational strain, is the limiting case at the other end. The active shear plane (*b*) is here horizontal. Ellipses *B*, *C*, and *D* represent cases intermediate between the two limits.

1. *Rotational Strains Developed by Bedding*

In the explanation worked out by Hayes for the Rome and Cartersville overthrusts of the southern Appalachians, the most important condition necessary for the development of such broad thrusts is stated to be the proper relation of rigidity of strata to superincumbent load.[1] An idea of the relative rigidity of the different strata in this portion of the Appalachians may be obtained from an inspection of the stratigraphic column. At the base of the exposed section are the Coosa shales which have a great, but unknown, total thickness and a minimum rigidity. Above these are several formations (Weisner quartzite, Rome sandstone, and Connasauga shale) of intermediate rigidity. These are then followed above by the Knox dolomite, a formation of unusual rigidity which consists of 3,500 to 4,500 feet of massive, cherty, dolomitic limestone almost wholly without bedding planes. Immediately upon this rest 1,200 to 1,800 feet of rigid Chickamauga limestone whose lower portion is nearly as massive as the Knox. There are, in these two formations, approximately 5,000 feet of strata with indistinct bedding and entirely without beds of shale. This gives them great competency when subjected to deformative stress. Above the Chickamauga limestone are several thin formations of lesser strength, followed by 2,500 feet of very weak Floyd shale. This very weak series is followed in turn by several formations of greater rigidity, namely the Oxmoor sandstone, Bangor limestone, and Coal Measure sandstone. This section may be generalized as follows:

D—Moderately strong sandstones and limestones.

C—Weak shales.

B—Very rigid, massive dolomites of greath strength.

A—At base very weak shales.

It is the great competency of the thick dolomites, operating in conjunction with the incompetent beds above and below, which has controlled the deformation according to Hayes.[2] Quoting from Hayes's explanation of his diagram (see Fig. 2):

> As already stated, the rigid mass *B* presents its weakest points where the compressing force exerts a shear across the beds—i.e., on the sides of the folds

[1] C. W. Hayes, *op. cit.*, pp. 150–52. [2] *Ibid.*, pp. 142–44.

H and *L*. But the point *H* is in the line of least resistance, since it is nearest to the region of application of the compressing force, and hence the mass of material to be moved is less than if the break were to occur at *L*. After passing the central rigid mass the line of least resistance follows the upper bed of minimum rigidity *C* till another fold is reached where it passes through the upper rigid bed *D*. Erosion of the latter might determine the point at which the line would emerge at the surface.[1]

The requisites of this type of overthrust are thus seen to be an alternation of formations of pronounced difference in competency, affected by slight folding and possibly by moderate erosion of the upper competent layer on the anticlines before the faulting commences.

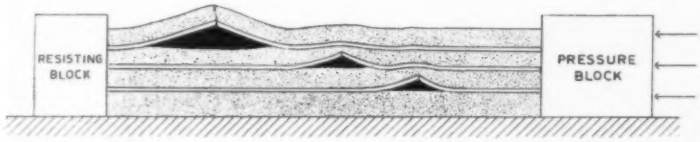


FIG. 8.—Arching up of competent layers when there is too much difference in the strength of the layers. The competent layers were composed of pure plaster, the weak layers of damp sand.

Experimentation: A single strong layer amid much weaker material.—To test experimentally some of these conclusions relative to the influence of a marked difference in the competency of neighboring layers upon the nature of their deformation, the crushing machine was loaded in the first set of tests with a single heavy, competent layer of plaster in the midst of weaker sandy layers above and below. When pressure was applied, the strong layer which carried most of the thrust commonly warped upward into a very low swell and then cracked at the top of the swell. With further compression the broken beds continued to arch up, leaving an open space below (Fig. 8). It did not appear to make much difference in its effectiveness whether the strong brittle bed were the top layer, or whether it were lower down in the series. If lower down and it was sufficiently competent, it still controlled the deformation and carried up the overlying weaker material with it.

[1] *Ibid.*, pp. 151–52.

Several strong layers between very much weaker ones.—When there were several strong layers between much weaker ones, similar arching was sometimes the result, if there was sufficient difference in the rigidity of the layers. But rather more commonly a strong tendency to dovetail was manifested. The strong and brittle beds of plaster were first thrust faulted, but in some cases the planes of faulting dipped toward the moving pressure block and in other cases away from it, thus giving both underthrusting and overthrusting (Fig. 9). After faulting commenced, the broken ends of the strong layers were wedged into the adjacent softer material, pushing it aside. Further compression caused an interwedging of

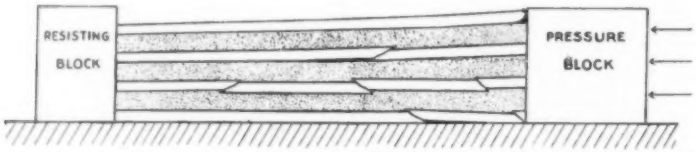


FIG. 9.—Development of dovetailing structure by both overthrusting and underthrusting when there is too much difference in the competency of the layers. With further compression the dovetailing becomes more pronounced. The strong layers were composed of four parts of clay and one of plaster; the weak layers were of damp sand.

the competent beds, producing a dovetailing structure. Dovetailing therefore results when there are a number of strong layers and the layers are too unequal in competency. This is commonly the case when there is an alternation of plaster layers and layers of damp sand. It even takes place when the competency of the strong layers is reduced by adding four parts of clay to one of plaster. This seems to be because the sand is very incoherent. When dovetailing does occur in experimentation, obviously not much is to be learned from the results so far as the present problem is concerned.

Less difference in competency.—The conditions of the last set of experiments apparently do not at all approach the conditions which control faulting in the earth. There was too great difference in the relative strength of the layers. The weak layers were too weak. For the next set of experiments sand was abandoned and only

mixtures of clay and plaster were used. Fairly good results were obtained by making the stronger layers of equal parts of plaster and clay and the weaker layers of one part of plaster to two parts of clay. There was then a working difference in competency, but at the same time not too great a difference to cause simple arching or the troublesome dovetailing.

Fracturing was found to take place at different angles across different beds. In general, it followed lower angles across the softer layers than across the stronger and more brittle ones. Perhaps the most typical result obtained is shown diagrammatically in

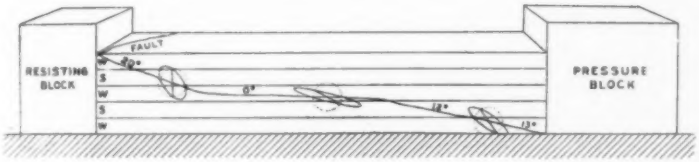


FIG. 10.—Drawing of experiment which shows how the inclination of the fracture plane may vary greatly in crossing beds of different competency. Because of the operation of a rotational strain following the fracturing of the brittle competent layers, there resulted nearly horizontal shearing through the weak, clayey layer. The strain ellipses are drawn upon the fracture line to illustrate the variable nature of the strain.

Strong layers (*S*) composed of equal parts of plaster and clay; weak layers (*W*) of one part plaster and two parts clay.

Fig. 10. When pressure was first applied in this experiment, the stronger layers carried most of the thrust, while the softer layers yielded and accommodated themselves so far as was necessary by compacting. With increasing strain the upper strong layer fractured at an angle averaging 20°, and this plane of fracture was projected through the overlying clay. With this fracturing a strong rotational strain developed below. This caused almost horizontal shearing through the soft clayey layer, where the prevailing angle of the fault plane is found to be less than 5°, and as a result of these shearing stresses the strong plaster layer below was faulted at 12°.

Bedding, therefore, where there is sufficient difference in the relative competency of the strata, may be an important factor in

determining low-angle faulting. As shown in Fig. 10, in which the ellipsoids representing the axes of strain are drawn upon the beds, the lowering of the angle in this way seems to be the result of shearing stresses and rotational strain. A difference in competency is thus one means of developing rotational strain, and the type of faulting described above comes under the category of rotational strain thus produced. The difference in competency may not be solely because of a difference in the kind of rock, but it may result also from a very unequal distribution of bedding planes which are planes of weakness. It is to be noted that an abundance of strongly marked, closely spaced bedding planes, in addition to making the competency of the formation less with respect to more massive adjacent formations, also makes splitting parallel to the bedding of the bedded rocks much easier than breaking across the bedding. With less resistance offered in that direction, fault planes crossing very thin bedded shales will be lowered to a certain extent toward parallelism with the bedding. The more bedding planes and the more pronounced they are, the lower the angle of faulting.

General discussion.—The Lewis overthrust in the Glacier National Park of Montana, according to the well-known explanation of Willis, who would classify it as an erosion thrust, appears to be a case of low-angle faulting controlled by bedding.[1] The fault plane, where observed, is located in the Proterozoic Altyn limestone, whose bedding it appears to parallel closely. Above the fracture plane, for the most part, are rigid, brittle, competent strata. What lies below the fault plane is not known, since the oldest formation in the vicinity is the Altyn limestone just above the fault plane. This has been overthrust upon the Cretaceous. In the explanation given by Willis, the sequence of events is, first, gentle folding by which there was developed a low, unsymmetrical anticline whose gentler west limb had a nearly constant westerly dip. Erosion then removed the crest of the fold, thus leaving the west limb a thick sheet of competent strata, unweakened by secondary flexures

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), p. 223 and Pl. LIV, Figs. 6 and 7; "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

and in a position to carry thrusts from the west. Because of the erosion of the crest of the anticline, support from the east limb had been to a considerable extent removed, and frontal resistance to a thrust from the west greatly reduced. With resistance in front lessened and resistance beneath unchanged, or very much less diminished, lateral thrusts developed shearing stresses which caused the overthrust. This type would, therefore, be an overthrust due to rotational strain fostered by the special attitude of the strata and especially by the lessening of the resistance to a forward movement of the upper layers because of preceding erosion. The shearing then took place along a bedding plane as a line of weakness.

The pretty structural explanation of the southern Appalachian overthrusts offered by Hayes was entirely dependent for its working qualities upon appropriate stratigraphic formations of widely different competency. Similarly, though to perhaps lesser degree, the erosion-thrust of Willis is dependent upon appropriate stratigraphy and antecedent history. Admitting that each of these explanations fits the particular case, or type of cases, for which it was devised (which was probably all that the authors intended), it is clear that an explanation on either of these lines cannot fit the type of overthrust which is so wonderfully displayed in the Scottish Highlands. In these remarkable dislocations the low-angle overthrusting did not occur until after the continuity of bedding over the overthrust area had been completely interrupted and displaced by repeated slice faults at the ordinary angle of 40° to 45°. The Scottish overthrusts did not follow any one weak formation, as did the overthrusts in the southern Appalachians, but cut straight through the various rocks of many previously faulted blocks. It is clear that a more general *raison d'être* for low-angle faulting must be sought.

2. *Rotational Strain in Homogeneous Material*

Piling up of material a possible factor.—One of the most characteristic features of the Caledonian diastrophism which produced the faulted structure of the Scottish Highlands was the development of a remarkable imbricate structure prior to breaking along the great thrust planes. It seems to be well established, both from the field

evidence and from Cadell's experiments, that the order of events was first slice faulting of the ordinary 45° angle type, and that, after a mass of slices had piled up in this manner, a low-angle thrust plane broke through the mass of slices and the whole mass above rode bodily forward on this plane as a "sole."[1]

Similarly it will be observed that the well-defined Rome overthrust in the southern Appalachians occurred in the midst of a

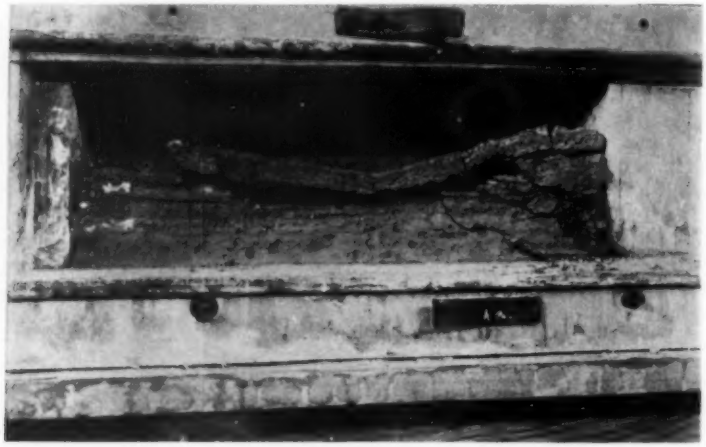


FIG. 11.—Slice faulting, developing an imbricate structure. The bottom layer was composed of pure clay; the next above of mixed sand and clay; the third was a thin layer of sand; and the heavy competent layer at the top was made of plaster two parts, sand one part and clay one part. The brittle top layer arched up and fractured as the first slice fault developed. Each successive slice fault broke out below and in front of its predecessor.

series of ordinary reverse faults. Directly south of the town of Rome, Georgia, there are mapped six large reverse faults just to the east of the line of the great overthrust. They are thus in the mass which traveled westward with the overthrust.[2] Similar slice faults in series, though they cannot be traced continuously into the par-

[1] J. Horne, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 471–76; H. M. Cadell, *op. cit.*, pp. 347–48.

[2] C. W. Hayes, *U.S. Geol. Surv. Geol. Atlas, Rome, Ga.*, Folio 78, 1902. Structure Section Sheet.

ticular breaks near Rome, are especially numerous in the same relation to the overthrust throughout the southwest portion of the quadrangle. Somewhat analogous relations are to be noted elsewhere. Directly in front of the Lewis thrust in Montana there is represented on the structure sections a series of slice faults formed as if in preparation for another overthrust which presumably, if the deformation had been carried further, would have broken through lower than the Lewis slip and to the east of it.[1]

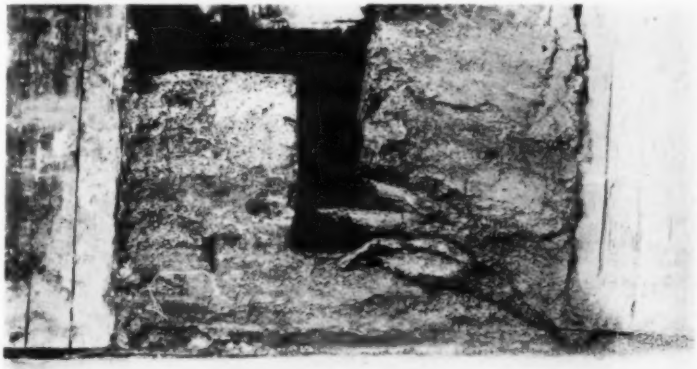


FIG. 12.—Deformation of specially shaped mass. Slice faulting resulted. In this particular experiment the pressure blocks were not held rigidly in place by controlling flanges, but were free to rise or become tilted.

A relationship between a piling up of rock masses and the development of the low-angle overthrust has therefore been suggested. It might at first seem possible that lateral thrusting applied upon the piled-up mass, thus bringing forces to bear in a higher plane than would be the case if there were no piling up, would, on the lever-arm principle, develop a rotational strain which would cause fracturing at a lowered angle. To test this question experimentally, there was molded in the box a homogeneous mixture of clay and plaster, which was high adjoining both pressure blocks and low in the middle. The rectangular

[1] Eugene Stebinger, "Geology and Coal Resources of Northern Teton County, Montana," *Bull. 621, U.S. Geol. Surv.*, 1916, Pl. XV.

outlines of the prepared block, by exaggerating any case of piling up likely in nature, ought not to fail to reproduce the low angles, if such be due to piled-up material acting in this way. The results are shown in Figs. 12 and 13. There was first slice faulting on the right-hand side, from which the pressure came. Each successive fault broke below the previous one as the mass was compressed more and more. This is similar to the experience of Cadell. As compression went on, the planes of the earlier faults became

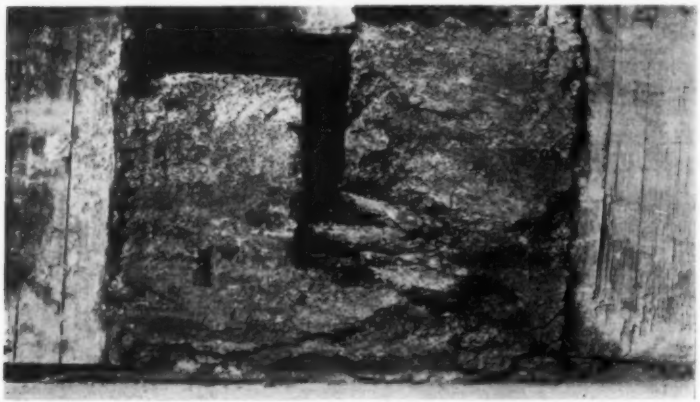


FIG. 13.—Same as Fig. 12. After further compression

distorted and obscured by the later deformation. At length a low-angle fracture broke through from the left, or resistance block side. This was no doubt determined by lines of least resistance due to weakening by the previous fracturing.

To test the matter further a mold of pure paraffine was prepared in essentially the same shape. The paraffine had the advantage of being more nearly homogeneous than the clay-plaster combination. In the two trials made, fracturing proceeded directly across the elbow at approximately 45° (Fig. 14). Lest the right-angled elbow might play an unsuspected part in determining the angle of splitting, paraffine was molded into a block having the shape shown in Fig. 15. When pressure was applied the block faulted at the farther end. It faulted at the farther end because

the force per square inch was greater there (owing to the smaller cross-section over which it was distributed) than at the other end near the pressure block where it was distributed over a larger area of cross-section. Rupture occurred where the intensity of stress was greatest, even though it was farthest removed from the pressure block. The fault averaged 42° for its whole length. The angle shows that it was caused by a non-rotational strain. The same was true also of the two previous tests. The shape of the block, at least to the extent of the variations tried in these experiments, apparently does not change the nature of the strain. But perhaps, after all, only a non-rotational strain could develop under

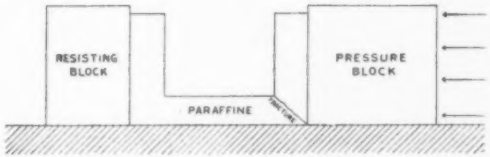


FIG. 14.—Block similar in shape to that shown in Figs. 12 and 13, but composed of paraffine. A 45° fracture developed.

the conditions of these experiments, since the pressure block is guided rigidly forward by the controlling flanges of the machine and so cannot turn. But one may conclude, nevertheless, that a piled-up mass having a higher standing cross-section to be pushed forward, does not, of itself, add a rotational element to the strain when laterally compressed, nor, so far as this principle is concerned, does it lower the angle of fracture.

How rotational strain develops fracture.—To show how a rotational strain will deform such a block as was used in the experiment just described, another block of paraffine was cast in the same mold and subjected to a rotational strain in the following manner. As before, the pressure was applied from the same long side, but instead of being applied against the whole surface of that side it was applied only to the upper half of it. The resisting block, as before, buttressed the whole of the shorter left-hand side. With the opposing forces acting horizontally at quite different elevations, a rotational couple was developed. As the strain slowly increased the paraffine

near the pressure block first yielded somewhat by plastic deformation. Then, as a result of the shearing stresses, it started to break along a very low angle of fracture near the bottom of the block (Fig. 16, break *A*). The experiment was stopped at this point and the block removed for study. After a rest of a few days the deformed block was again placed in the crushing machine and

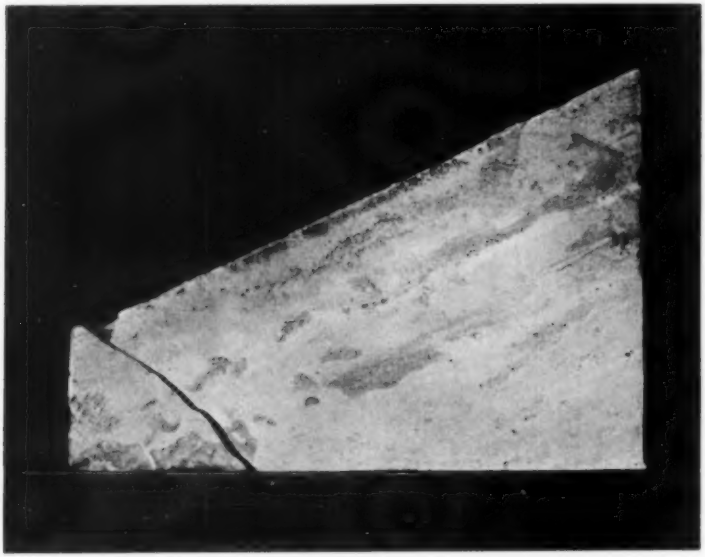


FIG. 15.—Deformation of specially shaped paraffine block under non-rotational strain. Pressure applied uniformly upon right-hand face. Fracture averages 42°.

pressure applied as before. But instead of further splitting along the old line of breakage near the bottom of the block, an entirely new break occurred at a much higher level (Fig. 16, break *B*). This new fracture extended completely across the block. Though irregular in detail, its general direction was very close to horizontal. To verify these results, a new block of paraffine was cast in the same mold and pressure was again applied in the same way. The result again was breakage along a nearly horizontal shearing plane (Fig. 16, break *C*). In breaking out at the surface, however, the fault plane,

in both cases, turned upward, producing a considerably steeper angle in the immediate vicinity of the surface.

Experiments therefore show that the effect of a strong rotational strain, even in homogeneous material, is to produce shearing and complete rupture, essentially parallel to the direction of the applied force. If the thrusting be in a horizontal direction, the plane of rupture will approach horizontality. In these experiments it was noted that the low-angle shearing required fewer turns of the screw and thus the application of less force than the 45° fracture from

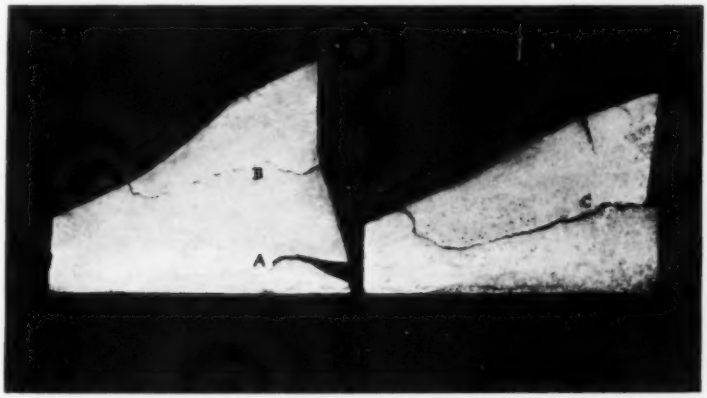


FIG. 16.—Deformation of paraffine blocks (same mold as block in Fig. 15) under rotational strain. Pressure applied only to the upper half of the right-hand face. The fracturing, though irregular, was not far from horizontal.

non-rotational strain. This merely bears out the well-known fact that the resistance of materials to shearing stresses is much less than to direct compressive stress. Hence the disposition to shear if conditions allow.

Lessening the resistance above.—Deformation by rotational strain may thus be developed in homogeneous material by sufficiently increasing the effective differential stress in the upper portion of the mass with respect to that in the lower portion. It is the greater unbalanced pressure in one portion over another which is effective. This unbalancing of pressure may be accomplished in several ways. Within the earth it may be produced either by increasing the lateral

thrusting in the upper portion or by lessening its resistance, while the lower portion remains unchanged. It may also be developed by diminishing the thrust below or by increasing the resistance in the lower part, while conditions in the upper portion remain essentially the same. Or it may be accomplished by some combination of these. The first process facilitates deformation in the upper part; the second retards deformation in the lower part. Whatever affects the ratio influences the character of the deformation. The greater the difference developed the greater the shearing tendency. The intensity of thrusts and the resistance at different horizons in the earth should therefore be a vital factor in determining shearing.

At the present time the location and intensity of lateral thrusts in the earth are so imperfectly understood that a treatment of that topic is reserved for further information. Rather more, however, is known concerning the resistance offered. Factors which either lessen the resistance above, or increase it below, may play a part in overthrust faulting.

The resistance above may be diminished in several ways. The erosion-thrust of Willis and Hayes already discussed is a clear-cut illustration of how it may be accomplished in heterogeneous materials. Resistance above is here reduced by erosion which removes the heavy, competent upper layers from the crest of an anticline. The resistance of the remnants of the upper layers to forward movement having been sufficiently diminished in this way, this more movable portion shears nearly horizontally along a bedding plane as a line of weakness (see Fig. 2). Shearing along bedding planes and the control of overthrusts by differences in the competency of the beds are related phenomena.

In homogeneous material the resistance above is lessened by other means. The experiments of Cadell indicated that before the low-angle overthrust occurred there was first slice faulting and the piling up of slices. Slice faulting to a remarkable extent was associated with the Scottish overthrusts and to a certain extent with those in the southern Appalachians. If the mere piling up of materials, as such, does not introduce a rotational element to the strain and so lower the angle of fracture, nevertheless the repeated slice faulting and moving of fault blocks do have an effect upon

the resistance of the faulted strip. The slicing and secondary shattering would seem to weaken the superficial sheet which has suffered the faulting. It may be perhaps that the superficial shell, freer to move as a general mass than it was before slicing, while the lower, deeper levels have not been equally affected by what has taken place, now finds it easiest to slide bodily forward over the less movable lower portion. If this be true, it would make the rupturing by the preparatory slice faulting far more important in the development of low-angle overthrusts than the piling up of material.

Greater resistance and drag below.—With horizontally directed compressive stresses in operation rotational strains would also tend to be produced by the co-operation of any factor which increased the resistance of the deeper portion of the rock mass involved, while the resistance of the more superficial portion to such stresses remained the same. The far-reaching experimental studies of Dr. Adams and his colleagues have shown that, on account of the increasing rigidity of the rocks due to cubical compression from the weight of overburden, resistance to deformation in the earth should increase with increasing depth below the surface.[1] It is concluded that with increasing depth greater and greater stress differences are required to deform the rocks. From this principle it would seem to be a legitimate deduction that, for a lateral thrust of given magnitude, rock deformation should take place more readily near the surface of the earth than at a greater depth beneath the surface, and that in any case (barring the effects of local heating, or liquefaction) deformation should become less with depth, unless the magnitude of the stress differences which cause the thrusting increases as rapidly with increasing depth as does the resistance offered by the rocks.[2]

[1] Frank D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1912), 97–118.

[2] Since this was written, the principle of increasing resistance to deformation with depth below the surface of the earth has been strongly affirmed by Adams and Bancroft as the result of further experimental researches. (See Frank D. Adams and J. Austen Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV [1917], 597–637. Also Louis Vessot King, "On the Mathematical Theory of Internal Friction and Limiting Strength of Rocks under Conditions of Stress Existing in the Interior of the Earth," *Jour. Geol.*, XXV [1917], 638–58.)

In general, so far as these principles hold, there should be a tendency, strong or feeble according to the quantitative factors, for surficial shearing over a less movable portion below. Rotational strains thus brought into being might conceivably in some cases be a primary cause of low-angle shearing, or in other instances might co-operate as a secondary factor with other more important causes in producing a similar result.

Many glaciers, notably those in North Greenland, have developed in places horizontal shearing planes which are often grouped into distinct zones.[1] The englacial drift is definitely arranged along these planes of movement, and this in turn influences the rate of melting on the steep edge of the glacier, so that these planes of shear have, in many instances, become very conspicuous. These lines of débris are especially prominent in the lee of an embossment of rock over which the glacier has just passed. In most cases the shearing planes may be interpreted as due to the greater resistance of the rock knobs below. They seem to be further developed by the increased load of débris in the lower part of the glacier and by drag on the bottom beneath the moving mass. The rotational strain thus engendered causes nearly horizontal slippage of the upper portion over the lower. Where formed in the lee of an embossment of rock another factor enters to increase the rotational element. The rock mass protects the lower portion of the glacier from much of the push which the upper portion is receiving.[2] Thus while the upper portion of the ice is free to move forward, not only is the resistance of the lower portion of the ice to forward motion increased, but at the same time the actual thrusting to which that portion is subjected is diminished.

C. E. Decker has described various minor folds and small thrust faults, mostly of Quaternary age, which affect the strata close to the surface in northeastern Ohio and northwestern Pennsylvania.[3] The fault planes of these thrusts are commonly inclined at low angles (Fig. 17). If their proximity to the surface is of real

[1] T. C. Chamberlin, "Glacial Studies in Greenland," *Bull. Geol. Soc. Amer.*, VI (1894), 203–10.

[2] T. C. Chamberlin, *op. cit.*, pp. 207–8.

[3] Charles E. Decker, unpublished manuscript.

significance, it would suggest a strong tendency of layers near the surface to shear over less movable layers below.

E. EFFECT OF WEIGHTING

Although the piling up of faulted slices does not of itself cause the development of rotational strain, when the mass is subjected to horizontal compression, it may indirectly bring about that result by weakening the resistance of the upper portion owing to the

FIG. 17.—Thrust fault in Chagrin shales. On Paine Creek, 6 miles east of Painesville, Ohio. Fault plane dips 15° S.W. Throw 1 ft., heave 2 ft. 11 in. Charles E. Decker.

preliminary fracturing. If, in addition, the mass piled up is of sufficient magnitude, it may theoretically affect the result in another way owing to the fact that the additional weight of the piled-up mass adds a new force at right angles to the horizontal thrust. Figure 18 will illustrate the behavior of this force. In this diagram the horizontal thrust was taken to be three times the vertical force due to gravity. The resultant of these two forces will be inclined downward 18° 26′ from the horizontal. Fracturing as the result of these two forces will be determined by the direction of this resultant of forces. As this is inclined 18° 26′ downward from the horizontal, faulting, even though it should take

place at an angle as high as 45° upward from the resultant of the forces, would still be only 26° 34′ from the horizontal. The relative magnitude of the horizontal thrusting force and the weight of the heaped-up mass determines how much the angle of faulting, under the given conditions, will be diminished from 45°. If the weight of the load gave a force equal to half that of the lateral thrust, the angle would be lowered because of this factor to the extent of 26° 34′, thus making it 18° 26′ from the horizontal. If the vertical force due to the extra load amounted to one-fourth the horizontal thrust, the angle of faulting would be lowered approximately 14° 2′, leaving it 30° 58′ from the horizontal. The resulting angle for the various stress ratios may readily be calculated.

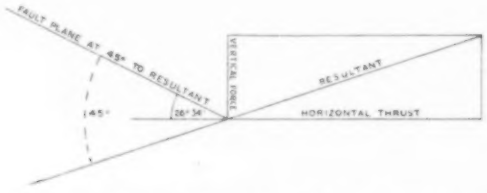


FIG. 18.—Diagram to illustrate the position of a fault plane inclined 45° to the resultant of forces. The horizontal thrust is here taken to be three times the vertical force. Result: the fault plane will be inclined 26° 34′ from the horizontal.

The effect of adding load, and hence additional force acting downward, is to subject the material under thrust to increased cubical compression. According to the principles so strikingly worked out by Adams and his colleagues, the effect of this should be to increase the internal resistance of the material and thus necessitate a much greater stress difference to initiate deformation than would be required without the additional load. Greater stress difference necessitates much greater lateral thrusts. As a result faulting may be hindered or even prevented altogether until much greater thrusts are developed. It may also, in consequence, be caused to take place elsewhere, as, for example, some distance beyond the edge of the loaded area. In our experiments with weighting the faulting most frequently appeared at the surface close to the border of the weighted portion, the fault plane dipping

under the heavily burdened portion (see Fig. 19). But in these experiments the loads were relatively light.

A load light in proportion to the horizontal stress will thus influence the angle of fracture, depending upon the ratio of vertical and horizontal stresses. A load very great in proportion to the horizontal stress will prevent faulting altogether within the loaded area. The influence of the load upon the angle of thrusting will therefore reach a maximum value somewhere between a load which

FIG. 19.—Effect of local weighting in locating the position of faults. The material to be faulted was clay stiffened with plaster; the added load was damp sand. In experiments of this sort the fracture plane most frequently appeared at the surface close to the edge of the piled-up overburden.

is light and a load which is heavy relative to the horizontal stress. What the proper ratio for the maximum effect will be cannot well be determined until more is known of the limiting strength of rocks under stress.[1] Some idea, however, may be gained possibly by a rough inspection of the factors involved. The stress difference necessary to cause faulting at a given depth in the earth would need to be sufficient to exceed the sum of the crushing strength of the given rock at the surface, plus the weight of overburden which must be lifted, plus again the increased strength of the material

[1] Louis V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Jour. Geol.*, XX (1912), 119–38.

resulting from the compression under the load. Suppose there were 10,000 feet of rock piled up above the plane along which the fault is to occur. Assuming a specific gravity of 2.7 for the rock, the pressure resulting from this column will amount to about 11,760 lbs. per square inch. If the stress along the axis of greatest stress, which is here horizontal, be taken to be three times this, it would need to be 35,280 lbs. per square inch. As the axis of least stress is vertical, the stress difference would amount to 23,520 lbs. per square inch. To cause faulting, this stress difference must equal the crushing strength of the rock under surface conditions augmented by the increased strength of the material induced by the hydrostatic pressure or cubical compression. This increased strength because of the depth is considerable, but pending more work of the type carried on by Adams and his colleagues this is not easily evaluated.[1]

However, this stress difference clearly would not be sufficient at this depth to deform the stronger rocks, like granite, and probably not rocks of average strength, though very likely it would be sufficient to deform the weaker rocks. Under these conditions, if the horizontal thrust were less than three times the vertically acting force, the stress difference would be proportionately still less effective in deformation. A ratio of more than three to one would, on the contrary, be more effective. A ratio of thrust to the weight of not less than three to one would seem to be required for extensive faulting through rock formations of average strength under a load ranging up to 10,000 feet of rock. This might lower the angle of faulting by 18° or less. But this reduction in angle from 45° falls far short of developing the approximately horizontal slippage planes of the great overthrusts. With loads greater than 10,000 feet of rock, the resistance of the underlying rock is still further increased. While the increase in resistance probably does not mount up in direct proportion to the increase in balanced pressure, nevertheless for any thicknesses of rock likely to be piled up by diastrophic agencies there probably would not be a very radical change in the ratio of axes of stress necessary for faulting. At

[1] More data are now available. See Frank D. Adams and J. Austen Bancroft, *Jour. Geol.*, XXV (1917), 597–637; also Louis Vessot King, *ibid.*, XXV (1917), 638–58.

best only a part of the lowering of the angle from 45° can be explained in this way.

If the low angle of the great overthrusts were solely a matter of load steadily accumulated by piling up slice fault blocks, then each successive slice fault should break through at a progressively lower angle. There should be a complete gradation from the first-formed fault near 45° to the final overthrust approaching horizontality. While some progressive lowering of the angle of the successive slice faults is to be noted in some Scottish Highland sections and elsewhere, nevertheless there appears to be a great final jump from the minor slice faults to the great horizontal overthrust.

F. RÉSUMÉ

The great overthrusts which are now coming to be recognized as a prevalent and commanding type of mountain structure are the result of conditions differing considerably from those which produce ordinary reverse faults. The distinguishing features of the overthrusts are the extremely low angle, which often approaches horizontality, and the very great displacement along the plane of slippage. The great displacement is made easier by the gentle slope of the fault plane. The low angle of the fault plane is the net result of the operation of several factors. Among the factors which will lower the angle of faulting from the theoretical 45° may be listed the following:

1. The normal or direct stress which, along planes inclined 45° to the line of application of the force, has an intensity as great as that of the tangential stress. It acts as a frictional resistance to shearing by the tangential stress. The lower the angle of the fracture plane, the less will be the frictional resistance due to the normal component of the stress. Hence the tendency to fracture at angles below 45°.

2. Rotational strain, which will lower one of the planes of no distortion (shearing plane) from 45° in pure non-rotational strain to 0° in the extreme case of rotational strain. Rotational strains may be developed from horizontal compressive stresses: (*a*) in homogeneous material: (1) by any factors which will increase the intensity of the tangential stress in the upper portion of the mass

undergoing thrusting with respect to that in the lower portion; (2) by any factors which will lessen the resistance in the surficial portion without proportionately changing that below; and (3) by any factors which will increase the resistance of the deeper portion of the zone subject to thrusting while the upper portion remains freer to yield; (*b*) in heterogeneous material by bedding, or similar structures, which present differences in competency of the right sort and thus call into operation some of the foregoing factors.

3. Preliminary piling up of material in the first stages of deformation, thus increasing the load and the vertically acting gravitative force. The combination of the horizontal thrusting force and the vertical gravitative force gives a resultant which is inclined downward from the horizontal. Even should faulting take place in a plane 45° from this resultant, it would still be inclined less than 45° from the horizontal.

4. Possible minor factors, as heterogeneity of material, length of deformed mass with respect to its other dimensions (after analogy of long column), shape of deformed mass, etc.

To these factors, operating in various combinations according to the individual peculiarities of each particular case, are attributed the low-angle fault planes of the great overthrusts.

THE HART MOUNTAIN OVERTHRUST AND ASSOCIATED STRUCTURES IN PARK COUNTY, WYOMING[1]

C. L. DAKE
Tulsa, Oklahoma

INTRODUCTION

Field work during the summer of 1916 brought to light what is believed to be one of the most interesting major thrusts yet described in the northern Rocky Mountains. So far as the writer is aware, the true nature of this fault has not heretofore been described, although Fisher[2] refers to it in discussing the structure of Hart Mountain. The area studied embraces a narrow strip of territory lying between the area covered by Fisher's Big Horn Basin report, just mentioned, and the Absaroka quadrangle on the west.

STRATIGRAPHY

The stratigraphy of the region is essentially the same as that given by Fisher in his above-mentioned paper describing the area adjacent on the east. The divisions of the Cretaceous adopted in mapping are those used by Lupton,[3] since they represent more detailed work than was done by Fisher. Hewett[4] has also described the stratigraphic column in some detail in the region immediately east of the area mapped by the writer. The following table of formations is largely compiled from the three reports mentioned above. Detailed description of the various stratigraphic units will not be given, except in the case of the so-called Fort Union(?) regarding the age of which there may be some question.

[1] Published by permission of the Wyoming State Geologist.

[2] C. A. Fisher, *U.S. Geol. Survey, Prof. Paper No. 53*, p. 37.

[3] Lupton, "Oil and Gas near Basin, Wyoming," *U.S. Geol. Survey, Bulletin 621L.*

[4] Hewett, "The Shoshone River Section," *U.S. Geol. Survey, Bulletin 541*, pp. 89–113.

Fort Union(?).—Since there is some uncertainty as to the age of the formation described under this name, and since upon this formation more than on any other depends the dating of the fault in question, it seems worth while to give a detailed description of its relations and lithologic character.

TABLE I

TABLE OF FORMATIONS

System	Formation	Characteristics	Thickness in Feet
Quaternary	.....	Glacial till and terrace gravels	?
Tertiary	.....	Andesitic breccias and lavas	?
Cretaceous or Tertiary	Fort Union(?)	Buff to yellow sandstones, conglomerates, red and gray shales	300+
Cretaceous	Cody	Gray to black shale, sandy near top	2,000
	Frontier	Gray sandstones and shales, with bentonite	500
	Thermopolis and Mowry	Gray and intensely black shales, with sandstone and bentonite	900
	Cloverly	Gray cross-bedded sandstone and shales	110
Jurassic or Cretaceous	Morrison	Variegated red, gray, maroon (etc.), shale, and sandstone	500
Jurassic	Sundance	Greenish-gray shales and sandstones and thin fossiliferous limestones	500
Permo-Trias	Chugwater	Red sandstones and shales with gypsum	750
Carboniferous	Embar	Massive gray limestone	100
	Tensleep	Massive gray sandstone and brown quartzite	100
	Amsden	Red shale and red to gray limestone	150
	Madison	Massive gray limestone, conglomeratic at the base in places	1,000
Ordovician	Bighorn	Massive gray limestone	300
Cambrian	Deadwood	Conglomerates, sandstone, and limestone	800
Pre-Cambrian	.....	Red granite, gneisses, and schists	?

It consists of an unmeasured thickness of alternating beds of yellow sandstone with red and white or gray clays. The sandstones vary from buff to bright yellow, and occur in several beds from 2 to 20 feet thick. They are cross-bedded on a large scale, and contain many concretions of brown sandstone varying from a few inches up to 10 feet or more in diameter. The concretions are harder than the matrix and weather out in large numbers, occurring abundantly over the surface of the ground. At many places the sandstones are finely conglomeratic, the pebbles averaging between one-fourth

and one-half inch in diameter. Red granite, basalt, quartzite, sandstone, black chert, brown chert, and shale make up the bulk of the pebbles. The shale members of the formation are dominantly gray, but contain many red layers. Thin lignitic seams were noted, but no leaves were found in a sufficient state of preservation to permit identification. One thin seam of black coal was found in the formation.

At one point the beds were seen to rest on the Cody with slight angular unconformity, although at several other points they partake of the folding of the older formations.

Though no fossils were found in these beds, the abundance of the red clays, the pebbly character, and the slight angular unconformity at the base all seem to favor correlation with what Hewett has called the Fort Union. It is true that Hewett has made no mention of the large concretions which are so abundant, and the writer noted similar ones from the basal Laramie of Fisher (Hewett's Gebo), not far to the east of the area mapped. At the same time similar concretions were noted, however, at a much higher horizon in Fisher's Laramie, in what is believed to represent Hewett's Fort Union. Fisher describes such concretions as occurring in the Laramie, but does not indicate the exact horizon.

Along the North Fork of Shoshone River these beds trace continuously into what Hague[1] has mapped as Pierre and Fox Hills. At the same point, however, Hewett[2] calls them "Tertiary sandstones and shales probably of Wasatch age." Structural reasons will be given later for believing that they are earlier than Wasatch.

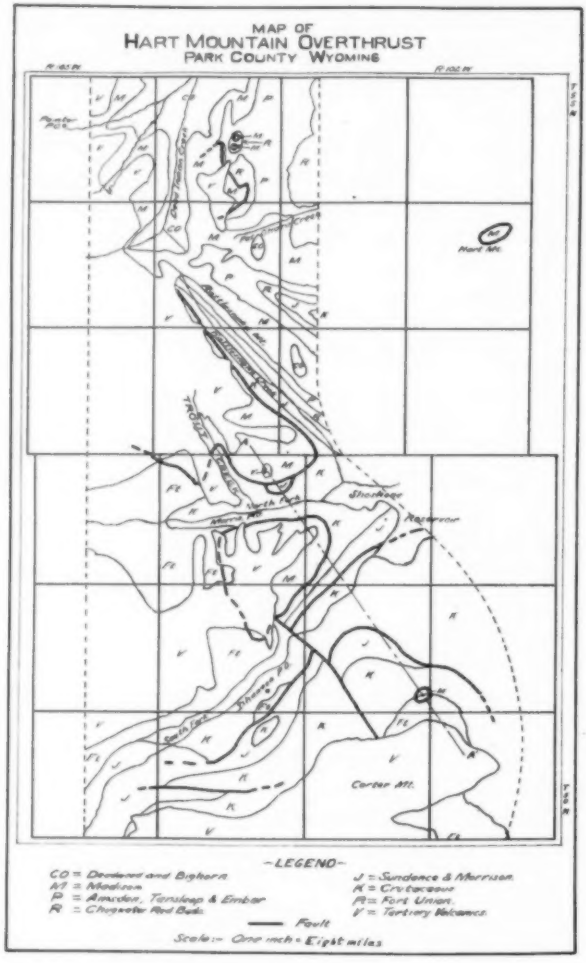
STRUCTURE

The major thrust.—The main plane of fracture occurs at or near the base of the Madison (Mississippian) limestone, which has been thrust out over beds varying in age from Madison to Fort Union(?). At the southernmost point, where the fault was located, the limestones rest on sandstones of Fort Union(?) age, but toward the north the stratigraphic throw decreases until at the northernmost

[1] Hague, Absaroka Folio, *U.S. Geol. Survey*, Folio 52.

[2] Hewett, "Sulphur Deposits in Park County, Wyoming," *U.S. Geol. Survey, Bulletin 450*, p. 478.

extremity the Madison rests on the Chugwater Red Beds. For the most part the Mississippian limestones are more resistant than



the beds on which they rest, and this condition results in a pronounced Madison escarpment along most of the course of the fault.

This escarpment is a very striking feature of the scenery along the Cody Road to Yellowstone Park, just west of the Shoshone Reservoir.

Traced westward up the valley the fault on either side passes beneath the Tertiary volcanics and is lost. It passes in a bold escarpment around the east end of the divide between the North and South forks of Shoshone River and extends for several miles up the north side of the latter valley, where it is again buried beneath the Tertiary breccias. It does not reappear on the south side of the valley of the South Fork except as an isolated peak of Madison resting on Fort Union(?) at the east end of Carter Mountain in Sec. 36, T. 51 N., R. 103 W. Several miles south of this point, however, abundant Madison bowlders are noted along the slopes on the east and southeast of Carter Mountain, indicating that the fault block of Madison probably occurs buried beneath the lavas of that mountain, or even possibly outcropping in small overlooked exposures along the lava scarp of that divide.

On the north side of the North Fork Valley the scarp makes a sharp re-entrant where Trout Creek cuts through the faulted block. In Sec. 6, T. 52 N., R. 103 W., the scarp bends abruptly northwestward and extends for a long distance along the west side of Rattlesnake valley, overlapped at several points by Tertiary volcanics, beneath which it passes at the head of the valley. In this distance the Madison rests on successively older beds, from Cody shale to Chugwater "Red Beds." The trace of the fault could not be found on the east side of Rattlesnake valley, from which the block of faulted Madison has probably been largely removed by later erosion. It is suspected that fragments of the block still remain on the top of Rattlesnake Mountain anticline, but if so they probably rest, Madison on Madison, and have not been detected. Along the divide between Rattlesnake valley, Pat O'Harra valley, and Dead Indian valley the trace of the fault plane could not be found, either because wholly removed by erosion or because Madison was faulted on Madison and not detected. In Sec. 3, T. 54 N., R. 104 W., the fault plane again emerges from beneath a small patch of Tertiary breccia and traces easily northwestward, to the point where the wagon road crosses Dead Indian Ridge, a distance

of four or five miles. Throughout this distance the Madison rests on the Red Beds. In Sec. 22, T. 55 N., R. 104 W., two prominent hills of Chugwater are capped with isolated patches of Madison.

In Sec. 16, T. 55 N., R. 104 W., the trace of the fault plane is lost, probably because it passes wholly into the Madison, where it is not easily detected. This view is supported by the fact that the Madison in this region appears to be excessively thick, as though repeated.

Not far from the center of T. 54 N., R. 102 W., occurs an isolated peak known as Hart Mountain. It consists of a cap of several hundred feet of Madison limestone, entirely surrounded by late Cretaceous and Tertiary sediments. It has been described[1] as due to a circular fault. Because this mass of Madison is entirely isolated in outcrop, it is not possible to demonstrate the continuity of the major thrust, just described, to this point. But the supposition hardly admits of doubt that Hart Mountain constitutes a portion of the large fault block so widely exposed to the west, especially in view of the similarity of stratigraphic units involved.

The extreme irregularity shown by the fault trace is largely due to erosion, in part to later deformation, since the fault plane dips at various but low angles at various points.

The north and south extent of the fault has been proved for over 25 miles in a straight line and for more than double that distance measured along the sinuosities of its course. Exclusive of the Hart Mountain outlier the easternmost and westernmost exposures are separated by a distance of 7 miles; including Hart Mountain, by about 16 miles. At the westernmost exposure the fault passes beneath the Tertiary andesites and is lost. At this point the Madison rests on the Fort Union (?), which in turn can be traced without break at least 6 miles farther west. If the movement was from the west eastward, as will be shown later, the fault plane must pass at least this far west, hidden below the lava, but cut through by erosion before the lava was poured out. If this is the case, the amount of displacement must have been not less than 22 miles, making no allowance for recession of the eastern front by erosion. Using average figures for the thickness of the beds involved, the vertical displacement is over 6,000 feet.

[1] C. A. Fisher, *loc. cit.*

There is nothing sufficiently regular about the dip of the fault plane to indicate the direction of movement. The fact, however, that the Cretaceous and Tertiary rocks in the Bighorn Basin to the east are continuous and but slightly disturbed for nearly 100 miles indicates plainly enough that the faulted block did not come from the east. The thick cap of volcanics to the west makes it impossible to expect any evidence in that direction, but in spite of that is seems clear enough that this block moved from west to east.

The South Fork thrust.—Along the lower valley of the South Fork of Shoshone River a second thrust fault is exposed on both sides of the valley, below the Hart Mountain thrust already described. As far as this fault could be traced, Sundance was found resting on Cody or Fort Union(?), and a section from the river level to the top of the ridge on the south side of the valley reveals the following situation:

Top
- Madison
- . . . . Major thrust
- Fort Union(?)
- Cody
- Frontier
- Thermopolis and Mowry
- Cloverly
- Morrison
- Sundance
- . . . . Minor thrust
- Cody

Bottom

On the north side the section is as follows:

Top
- Madison
- . . . . Major thrust
- Frontier
- Thermopolis and Mowry
- Cloverly
- Morrison
- Sundance
- . . . . Minor thrust
- Cody

Bottom

This fault seems to pass wholly into Cody shales both to the north and south and cannot be traced more than 6 or 8 miles. It probably shows again, in Sec. 11, T. 52 N., R. 104 W., on the north side of the North Fork, where abundant Sundance fossils are found on Cody shale slopes, just at the base of the main Madison scarp. It has a horizontal displacement approximating 10 miles, and a vertical movement of about 3,000 feet, or nearly 10,000 feet for the two faults combined.

Near the west line of T. 51 N., R. 103 W., the trace of this fault, which lies about S. 45 W., on both sides of the valley is suddenly lost in an area of intense brecciation, which is believed to mark the site of a transverse fault. The transverse fault seems to have shifted the trace of the thrust northwest about a mile, and west of the point of disturbance the thrust can be traced only on the south side of the valley. On the north side it is probably buried beneath Tertiary lavas. It has not been possible to prove the identity of the thrust planes east and west of the transverse area of disturbance, but the similarity of stratigraphic relationships [Sundance on Cody and Fort Union(?)] seems to indicate the possibility of the foregoing explanation.

The thrust plane appears to have been sharply folded along an axis lying about northeast and southwest, parallel to the trend of the South Fork Valley. At one point where a deep gorge cuts the axis of a sharply overturned anticline, not far south of Ishowooa Post-Office, yellow sandstones are exposed in a very small area beneath typical Sundance beds. The sandstones carry no fossils, but are similar in appearance to the Fort Union(?), and if of Fort Union(?) age the exposure represents a "Window" or "Fenster," such as has been described by several writers, in connection with major thrusts elsewhere.

Beartooth fault zone.—Along the eastern edge of the Beartooth Plateau, from the Clark Fork to the Montana line, is a zone of thrust faults, probably related to the same forces producing the faults already described though not continuous with them. The southern extremity of this zone lies about 8 miles north and 4 miles east of the northernmost point to which the Hart Mountain thrust was traced. This group of faults, all of which are associated with

overturned folds, in places carries the Pre-Cambrian granite out over the "Red Beds." The fault planes could not actually be observed, but are undoubtedly much steeper than the plane of the Hart Mountain thrust. The amount of horizontal displacement was not determined.

Mechanics of the faulting.—While no theoretical discussion of the mechanics of these great faults is proposed, it seems worth while to present some observations which may ultimately help to throw light on the problem:

1. The fault contact is practically everywhere concealed by talus from the Madison cliffs, but at several places it could be located within a few feet, and the zone of crush breccia is notably thin at most points.

2. The great limestone block above the fault plane is little folded. But while it presents the general aspect of a nearly flat-lying horizon, locally the dips are high, as a result of numerous small normal faults which appear to have been the result of the settling of the great block after the thrust ceased.

3. The soft shales below the major thrust plane, while much crumpled at places, are nearly horizontal and almost undisturbed over considerable areas where exposed by erosion several hundred feet lower than the major thrust.

HISTORY

The history of the faulting in this region depends, for its correct solution, on the careful determination of the age of the beds herein called Fort Union(?) and on a knowledge of the relation of these beds to the faulted block of Madison limestone. The second part of the problem is comparatively simple, and will be discussed first.

For long distances these beds occur at the foot of the Madison scarp, and there was little question from the very first that they passed beneath the Madison block. In view, however, of the statement of Hewett that these beds are probably of Wasatch age, it was thought possible that the sandstone might have been deposited, after the faulting and erosion, against the foot of the limestone scarp, since it was nowhere possible to find an actual contact of the Madison resting directly on the Fort Union(?).

If, however, the sandstones were laid down against the base of these high cliffs, they should contain a coarse and abundant angular limestone conglomerate, whereas a careful search nowhere revealed any Madison limestone in any of the sandstone of the formation. This constitutes abundant evidence that the Fort Union(?) actually passes beneath the fault block and does not lap against its foot.

As to the second problem, the exact age and equivalence of the beds called Fort Union(?), a less definite conclusion is possible. They are younger than the Cody, upon which they rest with slight angular unconformity at places. The fact that they are involved in the major faulting and folding makes it probable that they are not Wasatch, as Hewett has suggested, since beds of that age are known to cover similar major faults in Idaho.[1] The only other formations with which it seems at all possible to correlate them are Hewett's Gebo (Fisher's basal Laramie) or Hewett's Fort Union(?) (Fisher's upper Laramie), and to the writer the evidence seems in favor of the latter conclusion. If these beds are the equivalent of Hewett's Fort Union, it still remains to determine whether they represent the equivalent of the original Fort Union and whether they are very late Cretaceous or early Tertiary, problems with which this paper has nothing to do.

These faults involving the Fort Union(?) pass at many points beneath the Andesite, which Hague, in the Absaroka Folio, has called the Early Basic Breccia and which he considers to be of early Neocene age. This would date the faulting as taking place after the sedimentation of the Fort Union(?) and before the Neocene, probably in very early Tertiary time, since following the faulting long erosion had trenched the region deeply and in places completely cut away the fault block, before the Basic Breccia was laid down.

CORRELATION WITH OTHER FAULTS

Richards and Mansfield[2] have presented a concise statement of the available information regarding major thrusts in the northern Rocky Mountains, and hazard a possibility that these may consti-

[1] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust," *Jour. Geol.*, XX (1912), 704.

[2] *Op. cit.*

tute parts of one major thrust, carved into isolated portions by erosion. As they suggest, however, such correlation awaits further and more careful study, particularly as to the dating of the faults. To the information they have gathered may be added the more recent work of Haynes[1] on the "Lombard Overthrust" in Montana.

The present paper is presented as a further contribution to the subject, and, while conclusions as to correlation are still premature, the writer believes it to be quite improbable that these various faults will ultimately be found to be a part of one great overthrust. It seems much more likely that they represent numerous "Decken" or rock sheets, the one driven over the edge of the next after the manner described by Geikie[2] in discussions of Alp ne structure. Two such rock sheets, one above the other, are exposed along the South Fork of Shoshone River, in the area here described.

[1] *Jour. Geol.*, XXIV (1916), 269.

[2] Geikie, *Mountains, Their Origin, Growth, and Decay.*

THE ORIGIN OF VEINLETS IN THE SILURIAN AND DEVONIAN STRATA OF CENTRAL NEW YORK[1]

STEPHEN TABER
University of South Carolina, Columbia, South Carolina

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INTRODUCTION

Although the origin of metalliferous veins has long been of interest to the geologist and mining engineer, very few facts have been definitely established concerning the mechanics of vein formation. Direct investigation of the subject is difficult because of the complexity of the processes involved and because only the final results are available for examination. The evidence that may have existed during the early stages of vein growth has commonly been obliterated by alterations due to vein-forming solutions or to secondary changes. Most metalliferous veins are found in regions of dynamic metamorphism and where igneous processes have been active. Consequently these veins, as a rule, furnish little or no evidence relative to the mechanics of their origin. The study of small barren veins in regions of unaltered sedimentary rocks has been largely neglected because they are of no commercial importance, and yet such veins often furnish more positive evidence con-

[1] Presented in abstract at the Albany meeting of the Geological Society of America, December, 1916.

cerning the mechanics of vein formation than is to be found in the larger and more complex ones. It was for this reason that the present investigation was undertaken.

Many small veins are present in the Silurian and Devonian formations of central New York. These rocks are well exposed in the numerous limestone and gypsum quarries of Cayuga and Onondaga counties. In the summer of 1916 the writer visited all of the quarries now being worked in these counties and nearly all of those that are idle, but most of the data used in this paper were obtained in the extensive quarries found in the vicinity of Union Springs.

STRATIGRAPHIC FEATURES

The rock formations outcropping in the region studied are listed below:

Devonian
- Skaneateles shale
- Cardiff shale
- Marcellus shale
- Onondaga limestone
- Oriskany sandstone and conglomerate

Silurian
- Manlius limestone
- Roundout limestone
- Cobleskill limestone
- Bertie waterlime
- Camillus shale
- (Syracuse salt)
- Vernon shale

} Salina formation

Rock salt in the form of lens-shaped beds is present at many places immediately below the Camillus shale, but it has been removed in solution wherever the covering is less than about 1,000 feet thick, and therefore is never found near the outcrops of the strata.[1]

The Camillus shale contains intercalated beds of impure magnesian limestone and of gypsum. The limestone layers are more abundant in the upper part of the shale and probably represent

[1] D. H. Newland and Henry Leighton, "Gypsum Deposits of New York," *N.Y. State Museum Bull. 143*, 1910, p. 21.

transitional stages toward the Bertie waterlime. The gypsum is highly argillaceous and in places grades into gypsiferous shales. Partings of shale, ranging in thickness from a fraction of a centimeter up to several meters, are usually present, dividing the gypsum into several beds. These beds thin out and disappear, so that their number and thickness vary greatly in different districts. In many sections they are entirely absent. Gypsum may be found in small quantities all the way from the bottom to the top of the Camillus shale, but usually most of it is near the top.

The Onondaga limestone is commercially the most important of the limestone beds, and therefore there are many quarries located all along its outcrop; but the Cobleskill and Manlius limestones are also being quarried at several places. The lower layers of the Onondaga limestone, locally known as "gray limestone," have a well-developed crystalline texture similar to that of marble. The limestone forming the upper portion is bluish gray in color, dense, fine-grained, and contains numerous nodular concretions of chert or hornstone. Microscopic examination shows that the "blue limestone" consists essentially of irregular grains of calcite and small crystals of pyrite, while rhombic crystals of calcite may occasionally be distinguished.

The chert varies in color from light bluish gray to almost black, and on freshly fractured surfaces is often difficult to distinguish by color or texture from the inclosing limestone (see Fig. 6). It is irregularly distributed, occurring often in small isolated nodules, though more commonly the nodules are arranged in well-defined rows or layers, and in places these layers of disconnected nodules pass by gradation into more or less continuous and uniform layers or bedded veins, which may be 3 cm. or more in width and extend for distances of many meters. The chert masses have evidently been formed through replacement of the limestone, for some of them contain fossils in which the details of structure are perfectly preserved. On weathered surfaces the chert, because of greater resistance, stands out in sharp relief. Microscopically the chert is cryptocrystalline, and the boundary between limestone and chert is not sharply defined. In passing from limestone to chert there is a gradual though rapid decrease in calcite with a correspond-

ing increase in silica, but all of the chert examined contains numerous inclusions of calcite in the form of rhombohedral crystals (0.05 mm. and less in diameter), somewhat larger than the similar rhombs in the limestone.

STRUCTURAL FEATURES

The rock strata have been disturbed only slightly since their emergence from the sea. In general, the dip is toward the south at an average inclination of 7 to 10 m. per kilometer, but in a few places, because of gentle folding, there is locally considerable variation from this average.

Jointing is well developed throughout the area, and is probably due chiefly to the adjustment of strains resulting from folding and tilting. Appreciable openings are not found along these joints except near the surface, where, under favorable circumstances, they have been widened by the solvent action of descending surface water, and in such instances little or no deposition is to be observed on their walls. The fracturing of the rock strata seems to have resulted from compressive forces which would tend to prevent the formation of open fissures. The joints cut the veins of the region, and are therefore, in part at least, of later origin.

A thrust fault with displacement of a few centimeters is exposed in the Backus quarry, two miles north of Union Springs, and here the drag of the rock strata on both sides of the fault plane indicates that the displacement was accompanied by sufficient pressure to keep the fracture closed. A narrow vein of selenite follows this fault. Hopkins has described several thrust faults in the vicinity of Syracuse, the displacements ranging from a few centimeters to a little over a meter.[1]

Certain local disturbances of the rock strata, not noticeable in the overlying formations, may be observed in the Cobleskill limestone and the upper beds of the Salina. In places these strata have been pushed upward in such a way as to form low domelike elevations on which the joints sometimes have a radial arrangement. A group of six or more domes may be found a kilometer southeast

[1] T. C. Hopkins, "The Geology of the Syracuse Quadrangle," *N.Y. State Museum Bull. 171*, 1914, p. 29.

of Aurelius Station. They are strung out in a general north and south line near the bottom of a hill slope, and at the foot of the hill, close to the base of the domes, there are several large springs with deposits of calcareous tufa below them. A small quarry has been opened in one of the larger domes, which has a diameter of about 50 m. and height of 4 m.

Hartnagel[1] thinks that these domes are due to an increase in volume of the underlying beds, because of the formation of gypsum from anhydrite; but the present writer has found no evidence supporting this view. The shape of the domes, their location, and their general associations are such as to suggest that they have been formed in the same way as the salt and gypsum domes of Louisiana and elsewhere, which have been described and explained by Harris.[2] No open fissures, except where joints had been widened at the surface by weathering, and no veins were observed in any of the domes.

Open spaces of appreciable size are infrequent except in the upper beds of the Salina. The Bertie waterlime contains numerous small cavities attributed by Vanuxem to the solution of salt, since they sometimes exhibit the hopper-shaped outlines of halite crystals. The intercalated layers of magnesian limestone in the Camillus shale usually show the same porous structure and hopper-shaped casts. These cavities are frequently lined with a calcareous deposit. Small cavities, caused by the partial solution of fossils, are occasionally found in some of the limestones, and these openings are often lined with calcite, chalcedony, or crystals of quartz.

Open fissures of mechanical origin were found in only one locality, in Camillus shale exposed by a cut on the Lehigh Valley Railroad about 100 miles west of Cayuga Junction. The cracks are 1 cm. or more in width, and are partly filled with a calcareous deposit having the appearance of finely banded travertine or onyx marble, the layers of which are tinted various shades of light yellow and reddish brown. The material is similar in every way to the deposits lining cavities in the Bertie waterlime and to layers in

[1] C. A. Hartnagel, "Preliminary Observations on the Cobleskill ('Coralline') Limestone of New York," *N.Y. State Museum Bull. 69*, 1903, p. 1135.

[2] G. D. Harris, "The Geological Occurrence of Rock Salt in Louisiana and East Texas," *Econ. Geol.*, IV (1909), 12–34.

some of the calcareous tufa now forming in places on the surface. These fissures are possibly due to the solution and removal of underlying salt beds or perhaps to other superficial disturbances, since the deposits were evidently formed in the belt of weathering.

TYPES OF VEINS

Structurally the veins are of two different types: one fibrous, the other more or less coarsely crystalline and non-fibrous. The former are composed either of gypsum or calcite, the crystal fibers extending transverse to the strike of the veins, which run in all directions, but are generally parallel to the bedding. These veins are lenticular and continue for short distances only. The non-fibrous veins usually consist of gypsum or calcite, but the calcite veins sometimes contain accessory quartz and pyrite. They are more persistent and more uniform in width than the fibrous veins, and most of them are vertical or steeply inclined. The evidence indicates that each type had a different mode of formation.

SOURCE OF THE VEIN MINERALS

In the veins under consideration there can be no question as to the source of the vein minerals, for it is evident that they have been derived from the neighboring rocks. The veinlets found in the gypsum-bearing strata of the Salina are composed of gypsum, while those occurring in the limestones, waterlimes, and calcareous shales consist essentially of calcite. It is not the purpose of the writer, however, to imply that the vein minerals found in other and larger veins have usually had a similar source.

DESCRIPTION OF THE FIBROUS VEINS

The fibrous (satin spar) veins are larger and more abundant in the gypsum-bearing strata, probably because of the greater solubility of gypsum as compared with calcite. As a rule they are less than 3 cm. in width and from 20 to 50 cm. in length, but in places they have a width of over 10 cm. and extend for distances of many meters. Most of the veins are highly lenticular in form; where a vein thins out it may be replaced by another a little to one side, so that the ends overlap. Veins frequently split into two or

more branches, but the intersection of veins is extremely rare. When numerous they are commonly grouped to form linked-vein systems, as in Fig. 1. The vein fibers are usually normal to the inclosing walls, occasionally they are oblique, and very rarely they are curved or abruptly bent. In some veins most of the fibers apparently extend from wall to wall without a break, while in others there is a well-defined central parting frequently marked by the presence of inclusions of the wall rock. Small vugs are found in a

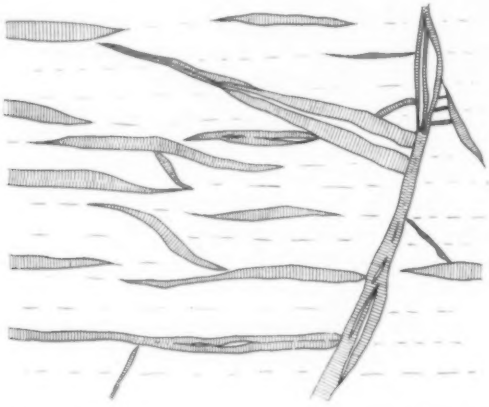

FIG. 1.—Veins of fibrous gypsum exposed in walls of quarry near Union Springs New York.

few veins, and these are lined with gypsum crystals of normal habit.

The veins of fibrous calcite are similar to those of fibrous gypsum except that ordinarily they are smaller and not so numerous. In both gypsum and calcite veins the fibrous structure is as highly developed in the larger veins as in those that are smaller, the diameter of the fibers apparently being independent of the size of the veins. However, the diameter of the crystal fibers does vary markedly with any change in the texture of the wall rock. In the fine-grained limestones and shales the fibers commonly have a diameter of 0.05 mm. and less, while in the Onondaga "gray limestone," with its coarsely crystalline texture, the diameters are as

great as 2 mm., and the fibrous structure is hardly noticeable in the narrower veins. Where veins of fibrous calcite in the Onondaga "blue limestone" pass through chert nodules, there is a sharp change in texture, the veins becoming coarsely crystalline and non-fibrous within the chert. This sudden change in texture is easily noticeable in veins that are less than a millimeter in width, when they are examined in thin sections under the microscope.

Where the veins are non-fibrous, the individual crystals usually have their longer dimensional axes parallel rather than transverse to the strike of the veins; and, especially in the smaller veins, most of the crystals extend from wall to wall. In the larger veins these crystals have maximum diameters of over 5 cm., while in the fibrous portion of the same veins the fiber crystals are uniformly 0.1 mm. or less in diameter. The larger crystals of calcite frequently show warped cleavages, and under the microscope undulatory extinction is common in these crystals and also in those of fibrous form. The fibrous crystals are very irregular in cross-section, since the prisms are not bounded by plane surfaces as is often true of the crystals found in the non-fibrous portions of the veins.

Vugs lined with calcite crystals of normal habit (simple rhombohedrons with some scalenohedrons) are occasionally present in the fibrous portion of the veins where the walls are of limestone, but they are more abundant where the veins are coarsely crystalline and have chert walls. The walls of the veins are sharply defined, and inclusions of the wall rock, limestone as well as chert, are common. When one wall of a vein contains angles or other irregularities, there are corresponding irregularities in the opposite wall, such that the two surfaces would fit closely together if placed in contact.

ORIGIN OF THE FIBROUS VEINS

In previous papers[1] the writer has cited evidence tending to prove that cross-fiber veins of the asbestiform minerals could not have been formed through any process of replacement or of recrystallization *in situ* and that they were not deposited in open fissures.

[1] Stephen Taber, "The Origin of Veins of the Asbestiform Minerals," *Proc. Nat. Acad. Sci.*, II (1916), 659–64; and "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1973–98.

Most of the objections raised against these theories of vein formation are equally applicable in the case of the veins of fibrous calcite and gypsum; and, in the descriptions given above, much confirmatory evidence may be found. All of the structural features characteristic of these veins have been duplicated in fibrous veins grown in the laboratory where their origin and growth could be observed in detail.[1] In view of all the facts obtained from field investigations and laboratory experiments, the conclusion is inevitable that the veins of fibrous calcite and gypsum have been formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the inclosing walls, and that the fibrous structure is due to the circumstance that the material for crystal growth was accessible in only one direction.

Calcite and gypsum are not normally fibrous, and wherever they have developed this structure it is due to the physical conditions which have prevented crystal growth, except in one direction. Merrill has described fibrous incrustations of gypsum forming on the walls of caves, and notes that the growing crystals not infrequently force off pieces of the limestone of considerable size.[2]

Laboratory experiments and field investigations indicate that the essential conditions for the growth of fibrous minerals, such as calcite and gypsum, are: (1) the growing crystals must be in contact at their base with a supersaturated solution; and (2) the solution must be supplied through closely spaced capillary or subcapillary openings in the surface of the wall rock. In the fine-grained limestones and shales the constituent particles are relatively small, and therefore the open spaces which are chiefly subcapillary in size are closely spaced; but in the crystalline "gray limestone" with its coarser texture these openings while no larger are necessarily more widely spaced. This explains the coarse texture of the fibrous veins occurring in the "gray limestone." The coarsely crystalline non-fibrous structure of veins where they pass through chert masses is due to the relative impermeability of the chert which has here

[1] Taber, "The Origin of Veins of the Asbestiform Minerals," *Proc. Nat. Acad. Sci.*, II (1916), 659–64; and "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1973–98.

[2] G. P. Merrill, "On the Formation of Stalactites and Gypsum Incrustations in Caves," *Proc. U.S. Nat. Mus.*, XVII (1894), 81.

prevented the addition of new material directly through the walls, thus forcing it to reach the growing crystals by diffusing between the walls. Vugs result from a deficiency of material necessary for growth because of insufficient concentration or because of relative inaccessibility. The latter probably explains the greater abundance of vugs between chert walls.

DESCRIPTION OF THE NON-FIBROUS VEINS

The non-fibrous veins range up to 5 cm. or more in width and in some instances are exposed for distances of 15 or 20 m. along the strike. Where they pinch out and disappear, they are sometimes replaced by others a few centimeters to one side or farther along the line of strike. Such vein systems may be traced for over 50 m. The veins show no appreciable change in appearance where they pass from one rock to another of different texture or composition. A vein exposed in the limestone quarry near Farleys can be traced upward through the argillaceous Manlius limestone, 20 cm. of Oriskany conglomerate, and into the Onondaga limestone, yet at no place is any variation in its appearance perceptible.

The vein walls are sharply defined, and fracture usually takes place more readily along the contact between vein and wall rock than in other directions. The opposite walls of a vein are parallel even when they are very irregular, and they would therefore fit intimately together if placed in contact (see Fig. 2). Angular fragments of the wall rock are occasionally present in the veins; and in many instances, by making parallel sections, it is possible to prove that they are in contact neither with other fragments nor with the walls. Most of the fragments show no evidence of rotation although they have been displaced through distances of 2 cm. or more (see Fig. 3). In places a fragment adhering to both walls of a vein appears to have been separated into several fragments by continued vein growth, as in Fig. 4.

Some veins have a banded structure with coarsely crystalline non-fibrous calcite in the center and a band of fibrous calcite along each wall. This is probably due to two stages of vein growth, as is indicated by the veins sketched in Fig. 2. Other veins are roughly banded, with pyrite along the walls and calcite in the center (see

Fig. 5), but in such cases the pyrite was deposited subsequent to the deposition of most of the calcite, and well-formed cubes and pyritohedrons may be found replacing impartially vein calcite and wall rock. Small seams of pyrite in places cut directly across the veins.

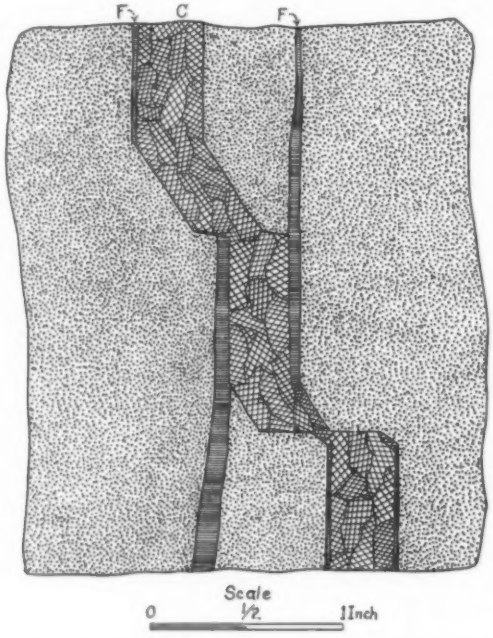

FIG. 2.—Calcite veins in limestone. Coarsely crystalline calcite (*C*) and fibrous calcite (*F*).

ORIGIN OF THE NON-FIBROUS VEINS

The facts cited above preclude the theory that these veins are due to recrystallization of country rock *in situ* or that they could have been formed through replacement; and the presence of detached inclusions of wall rock argues against the hypothesis that the veins were deposited in open fissures. If the veins were formed as a result of fissure filling, deposition of vein matter must have begun on the walls and continued inward until the opposite sides

met, thus forming a suture line near the center, but there is no evidence that such a suture was ever present in any of the veins under consideration. Large calcite crystals commonly extend without interruption from wall to wall, and in one vein a well-formed crystal of quartz, with a pyramid at each end of the prism,

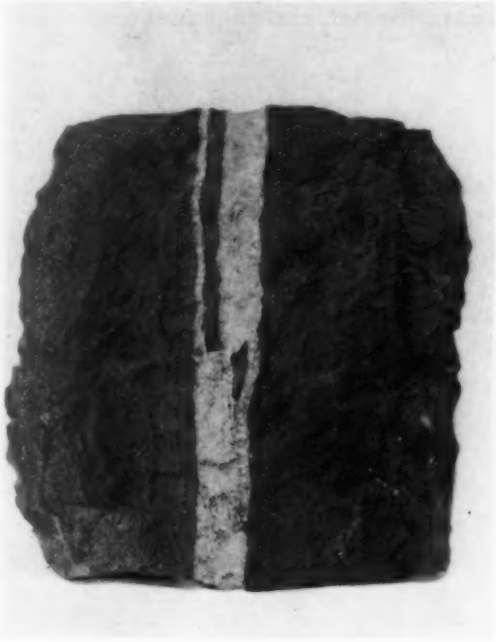

FIG. 3.—Calcite vein in limestone showing angular inclusion of the wall rock. Two-thirds natural size.

was found extending across almost the entire width of the vein (see Fig. 5).

The best evidence bearing on the origin of the veins is, perhaps, furnished by certain chert nodules containing veinlets of calcite, ranging up to 2 or 3 mm. in width, which do not extend into the inclosing limestone (see Fig. 6). The force separating the chert walls was applied so gradually that any stresses set up in the

limestone were adjusted by recrystallization, in the same way that slabs of marble or limestone may be slowly deformed under forces acting through a long period of time. This process probably also explains the curving walls of the lenticular veins.

The facts here listed are difficult or impossible of explanation under any of the hitherto generally accepted theories of vein formation. They are, however, easily explained on the hypothesis that

FIG. 4.—Calcite veins in limestone showing inclusions of the wall rock. Two-thirds natural size.

the vein-forming solutions entered along fractures, bedding planes, or other planes of weakness, where the openings were chiefly capillary or subcapillary in size; and that the separation of the vein minerals from solution was accompanied by the development of a force sufficient in magnitude to push apart the walls, and thus gradually make room for the growing veins. Circulation of solution through such narrow openings must necessarily be extremely slow, and under these conditions diffusion through the solution becomes an important factor in supplying additional material to the growing crystals.

Where veins pass through chert masses, most of the calcite crystals extend from wall to wall, and are oriented with their longer dimensional axes parallel rather than transverse to the vein walls—a fact that is likewise true of many non-fibrous veins in limestone and shale. Since this may be observed in the largest as well as the smallest veins, it means that the average number of vein crystals

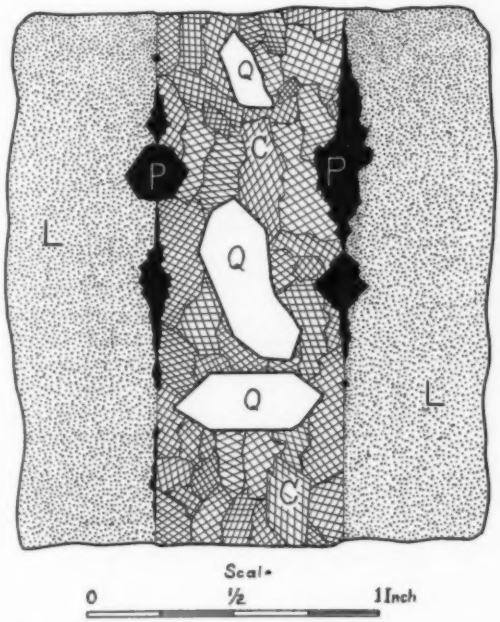

FIG. 5.—Vein consisting of calcite (*C*), pyrite (*P*), and quartz (*Q*), with walls of limestone (*L*). The pyrite replaces both the limestone and the vein calcite.

in contact with unit area of the wall tends to decrease with the growth of the vein. In other words, it is believed that with continued growth those crystals having any advantage, because of greater size, or more favorable orientation or location, tend to increase in size partly at the expense of their less fortunate neighbors. This conclusion is supported by the manner in which the inclusions have been displaced in some of the veins. The

enlargement of certain crystals at the expense of others does not, however, continue indefinitely.

NATURE OF FORCES THAT SEPARATED THE VEIN WALLS

It has been demonstrated that under suitable conditions crystal growth is accompanied by the development of a force which may even exceed the crushing strength of the crystals. The nature of

FIG. 6.—Chert nodule containing calcite veinlets which do not pass into the inclosing limestone. Two-thirds natural size.

this force has been discussed in several recent papers. Bruhns and Mecklenburg ascribe the pressure effects accompanying crystal growth to the "forces of adsorption and capillarity."[1] This has been refuted by Becker and Day and independently by the present writer. Becker and Day published a paper "with the purpose of demonstrating . . . . the existence of a linear force, apart from the volume expansion, exerted by growing crystals." They conclude (1) that

[1] W. Bruhns and Werner Mecklenburg, "Über die sogenannte 'Kristallisationskraft,'" *Jahresbericht der Niedersächsischen geologischen Vereins zu Hanover*, VI (1913), 106–8.

this force enables a crystal to grow in directions in which growth is opposed by external force "notwithstanding unrestricted opportunity for growth in other directions; (2) that the linear force thus exerted is of the order of magnitude of the breaking strength of the crystal."[1] Most of the phenomena that have been cited in support of the latter hypothesis may be explained, however, by the fact that the growing crystals have been in contact with a supersaturated solution in only one direction, or that the concentration of the solution has been greater in one direction than in others. The present writer believes that the pressure effects accompanying crystal growth are to be attributed chiefly to the molecular forces associated with the separation of solids from solution, and that the tendency to develop crystal faces is of minor importance.[2] Argument in support of this hypothesis has been given elsewhere.[3]

According to the writer's concept, the pressure developed during crystal growth is due, in most cases, to the fact that the solid can diffuse through a solution occupying small capillary or subcapillary spaces, while the crystalline mass built up by the separation of the solid from solution cannot escape through the small openings in like manner, even when under great pressure. The force observed during the separation of crystals from solution is believed to be analogous to the pressure developed when an anhydrous salt, confined in a limited space, combines with water that has diffused as vapor through capillary openings.[4] The diffusion of the solid through the solution is ascribed to osmotic pressure, and its separation therefrom to the relation between osmotic pressure and solution pressure.

Crystals grow through the addition of layers of material to their outer surfaces, and this can take place only when the surfaces are in contact with a layer of supersaturated solution, the concentration

[1] G. F. Becker and A. L. Day, "Note on the Linear Force of Growing Crystals," *Jour. Geol.*, XXIV (1916), 313.

[2] Stephen Taber, "The Growth of Crystals under External Pressure," *Am. Jour. Sci.*, Series 4, XLI (1916), 553–54.

[3] Stephen Taber, "Pressure Phenomena Accompanying the Growth of Crystals," *Proc. Nat. Acad. Sci.*, III (1917), 297–302.

[4] Stephen Taber, "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1986–87.

of which is maintained by diffusion from without. When a crystal grows in a direction in which growth is opposed by external pressure, the pressure is transmitted through a thin layer of solution separating the crystal from the foreign body. The effect of pressure and of capillarity, if the latter be present, is to reduce the thickness of this layer to a minimum; but it would be difficult, if not impossible, to completely expel it by pressure alone from between two smooth parallel surfaces. And crystal growth would tend to make the surfaces under pressure parallel, for deposition would be most rapid where diffusion is least restricted, i.e., where the layer of solution is thickest. Therefore a crystal growing in a limited space may make room for itself by forcibly enlarging this space, if it is supplied with the material for growth by diffusion through solutions occupying spaces that are sufficiently small.

The solubility of most substances, including calcite, is increased by pressure, and when such a substance separates from solution, there is an increase in volume which may result in pressures greatly exceeding the crushing strength of the crystals, provided the solution cannot readily escape. If the material that incloses a growing crystal is rendered more soluble by pressure, it may be gradually removed in solution as the crystals are enlarged. This probably explains the replacement of limestone and vein calcite by the idiomorphic crystals of pyrite.

The tendency of a crystal to assume a regular polyhedral form is important as a factor in the development of pressure during crystal growth only in so far as it affects the relative solubility of the crystal in different directions. While the difference in the pressure that may be developed in any two directions during the growth of a crystal is probably small, it can accomplish appreciable results if continued through a long enough period of time.

SUMMARY AND CONCLUSIONS

The small and relatively simple veins of a region of unaltered sedimentary rock were studied in order to obtain field evidence bearing on the mechanics of vein formation. Two types of veins are described, one fibrous and the other coarsely crystalline and non-fibrous. Both consist essentially of calcite or of gypsum.

According to the author's theory, the fibrous veins owe their peculiar structure to the fact that the material for growth was supplied only to the base of the growing crystals through solutions occupying closely spaced capillary or subcapillary openings in the walls, while the non-fibrous veins were deposited from solutions that entered between the walls of narrow capillary fractures and bedding planes. Because of the slow rate of circulation through such minute spaces, diffusion through the solution is probably an important factor in supplying material to the growing veins.

The diameter of the calcite and gypsum fibers varies with the spacing of the openings through which the material for their growth is supplied, and is independent of the size of the veins. There is evidence of some recrystallization within the non-fibrous veins during the process of growth, as a result of which those crystals that for any reason are less stable than their neighbors are redissolved, thus furnishing additional material for the growth of others.

The field evidence, confirmed by laboratory experiments, indicates that the veins were not deposited in pre-existing openings, but that the growing veins have made room for themselves by pushing apart the inclosing walls. The presence of drusy cavities, banding, or crustification are not in themselves proof that a vein was deposited in a pre-existing open fissure.

The force that enables a growing vein to make room for itself is attributed chiefly to the molecular forces associated with the separation of solids from solution.

TRANSPORTATION OF DÉBRIS BY ICEBERGS

O. D. VON ENGELN
Geological Department, Physiography Laboratory, Cornell University

Introduction.—On the east valley side of the southern end of the Cayuga Lake Valley, just to the north of Ithaca, New York, occur considerable areas of lake-clay deposits laid down when the waters of the lake were ponded to higher levels by the ice barrier of the retreating front of the last advance of the continental ice sheet. These lake-clay deposits are especially well developed in the zones marginal to the outer fronts of the higher-level deltas of streams tributary to the Cayuga Valley, and undoubtedly represent, in such cases, the extension of the bottom-set beds of the delta accumulations. The particular occurrence to which reference is made in this article is found at a level of 840 feet to the south and west of the top of a notable delta deposit of Fall Creek, having an average elevation of 930 feet (the block diagram, Fig. 1, illustrates the geography of the occurrence). Thus the clay may be assumed to have been laid down in water having a depth of 90 feet and removed from the nearest point of the steep front of the delta deposit by a little less than one-fourth mile. At the time when the delta and clay deposits were made the ice barrier must still have existed within the confines of the Cayuga Lake Valley, for the level of the delta top indicates that its building must have been coincident with the outflow of the lake waters across the north-south divide between Cayuga and Seneca Lake valleys, and the overflow of their combined waters was at a present elevation of 900 feet from the south end of the Seneca Lake Valley into the Chemung River and thus into the Susquehanna. On the other hand, it is unlikely that the ice barrier was immediately adjacent to the delta and lake-clay deposits, for the nearest point of the north-south divide with a low enough elevation to permit of a flow of water from the one lake valley to the other is found approximately 15 miles to the north

of their occurrence. To the south the divide is at every point much higher than 900 feet. Unless, therefore, the ice front is conceived as a long projecting point occupying the center of the lake valley and margined by lake waters on both sides for a considerable distance, the ice barrier should be placed comparatively remote from the site of the clay deposit. This concept is also in accord with observation of tidal and marginal-lake ice fronts in Alaska—there is an almost straight line truncation of the ice where it is fronted

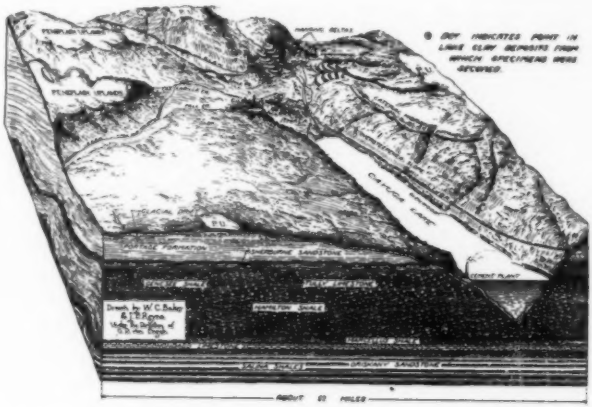

FIG. 1.—Block diagram of the region around the southern end of Cayuga Lake, New York.

by deep water. Again, the lake clay at the occurrence described has a thickness of at least 10 feet, and perhaps double that, with perfect, undisturbed stratification indicating a relatively long-continued period of deposition unaffected by minor oscillations of the ice front.

Purpose of paper.—It is the purpose of this paper to recount the recovery of rock material from a limited area and depth of this lake clay, to indicate the amount and character of this material, to account for its presence, and to make certain deductions from these facts with regard to the character and effectiveness of the erosive activities of glacial ice.

Recovery and nature of material.—In the course of gardening operations a trench approximately 25 feet long, 4 feet wide, and 3 feet deep was made in the lake clay. The clay deposit continued right up to the surface and was undisturbed and unmodified except for the top 12 or 16 inches that had been rendered more friable and amorphous in structure by plant growth and tillage. Below that the clay was exceedingly compact, fine grained, and slightly jointed with one-half- to one-inch spacing. From this clay, below the soil

FIG. 2.—Iceberg-dropped bowlders recovered from lake-clay deposit. Smaller pile apparently from single berg. Those marked *A* are striated or soled. Left to right diameter of bowlder at top of small pile is three inches.

layer, were dug the bowlders illustrated in Fig. 2. For the most part these were found in clusters of from three to five or more specimens occurring near each other. The bowlders in the smaller pile in Fig. 2 were all clustered within some 3 cubic feet of the clay at about the same depth. The total weight of all the bowlders is 74.5 pounds, of those in the smaller pile 8.5 pounds. In addition there were no doubt other rather large-sized bowlders that were overlooked, as no effort was made to go over the material with extreme care; and many observed smaller pebbles were not preserved. In any event the actual mass of the material present within the space excavated has no special significance; the figures are quoted merely to give some idea of the quantity of such bowlder

inclusions within the particular section of the clay that was examined. Possibly adjacent areas might have much greater masses, but the probability (as indicated by inspection of other near-by excavations) is that the average number would be lower, though occasional very large bowlders might make the mass as great, or greater, per average cubic foot of clay. It should be noted that away from the spots where the clustered bowlders occurred the clay was almost absolutely free from sand or grit.

Two distinctive charactersitics are immediately apparent on inspection of the material: (1) Many of the specimens (26 per cent of their number) show signs of glacial grinding, have striations, are "soled," or rudely faceted. In Fig. 2 a number of these are indicated by the letter *A*. (2) Much of the material (55 per cent by number, 67 per cent by weight) is from quite distant outcrops, that is, of rock material not available at the surface for a distance of 50 miles or more to the north even if the bottom of the lake is taken into consideration. Twenty-two of the 125 bowlders come from so distant a source as the Adirondacks or perhaps from Canada. There are 3 granites, 1 syenite, 12 gneissic, and 6 schistose specimens irrespective of size. Very prominent in the foreign material are Medina sandstones and Potsdam sandstones and conglomerates; of these three varieties there are 46 specimens. With one exception the large fragments, in general, are of the more resistant rock kinds from distant sources. The exception is a notably large piece of local sandstone derivable from bedrock outcrops extending from the area of the clay deposit to 10 or more miles to the north. This large local specimen is very conspicuously ground off on one side.

Source of the bowlders.—The only feasible explanation of the occurrence of these large rock fragments interbedded with the fine clay is that they are iceberg droppings. Icebergs, calved from the relatively distant glacier front, floated over the areas on which the clay was depositing and, on sufficient melting, dropped their rock load into the fine clay sediment, later deposits of which buried them completely. The bergs do not seem to have been grounded, for there is no apparent disturbance of the clay layering, though the clay material is so fine that in its oozy, under-water condition it

may have been too fluid to register so temporary a disturbance as the rocking and melting of a stranded berg.

Almost similar conditions of deposit of débris by icebergs have been observed on a tidal flat adjacent to the end of the Columbia Glacier, Alaska. There, at low tide, were exposed wide areas of fine-grained clay deposits. All over the surface of these clay deposits were scattered "nests" of glacial bowlders deposited by icebergs (calved from the adjacent Columbia Glacier) that had floated over the area at high tide (Fig. 3). The streaks on the mud

FIG. 3.—Bowlders dropped by icebergs on tidal mud flat adjacent to front of Columbia Glacier, Alaska. Streaks are due to the dragging of the bottoms of bergs floating in and out with the flow and ebb of the tide.

are occasioned by the dragging of partly floating bergs with the ebb of the tide. Similar "nests" of iceberg-deposited bowlders were a common feature on the sand beaches of the west side of Yakutat Bay, Alaska (Fig. 4). Here the pits in which the bowlders are nested are conspicuous because successive tides rocked the stranded bergs (Fig. 5) back and forth sufficiently to make quite an excavation before the ice melted completely.

Significance of observations.—From the foregoing observations of deposits adjacent to Pleistocene ice fronts and near living glaciers it is apparent that icebergs can and do carry notable quantities of

rocky débris and may deposit this at considerable distances from the calving end of the glacier. The fact that so large a percentage of the bowlders found in the clay deposit showed evidence of wear indicates that the material was largely derived from the bottom ice of the glacier. In fact, in collecting specimens of glacially striated pebbles, it is the common practice in this locality to resort to a deposit of glacial-lake clay for the material, as a large proportion of the bowlders found in such deposits exhibited these markings remarkably well preserved. Assuming that each of the bowlder

FIG. 4.—"Nests" due to rocking of stranded icebergs. Pebbles and bowlders on the surface of the sand and in the pits were included in the ice and deposited on its partial or complete melting. West side of Yakutat Bay, Alaska.

"pockets" in the clay is the result of the melting down of a single berg (and this seems very clearly to have been true of the material included in the smaller pile of Fig. 2 at least), it follows that the bottom ice must have been quite thickly shod with rock fragments. In other words, the material in transport at the bottom of the ice in any one cross-section must have been of considerable mass, and this material could have been acquired only by actual ice erosion of the bedrock over which it passed. Such being the case, the striking absence of local rock material in these iceberg deposits acquires a particular significance. It would appear that the local

rock material, being of comparatively slight resistance to grinding (mostly shales and thin bedded sandstones, commonly argillaceous), is reduced to rock flour almost immediately, while the resistant quartzitic and igneous material from distant sources survives. An alternative interpretation is that the local material of little resistant nature is not much subject to plucking, is eroded only by grinding, hence yields few sizable fragments. The same conclusion is suggested by the fact that the large-sized surface and near-surface erratics of local origin in the glacial deposits of the area about

FIG. 5.—Stranded icebergs, showing some with included débris. West side of Yakutat Bay, Alaska.

Ithaca, New York, are in very high percentage fragments of the Tully limestone, which outcrops in relatively massive layers, 2 to 10 feet thick, about 4 miles to the north of Ithaca and at other points more remote. It is also of interest to note that these large Tully erratics are in almost every case very conspicuously smoothed by ice wear and have usually the appearance of having lost a considerable part of their mass by such grinding, though it is of course commonly rather difficult to estimate how large the plucked block was originally. That the single large, local sandstone fragment found in the clay deposit was also very notably ground off is evi-

dence of the same kind. Specifically the fact that both the Tully limestone erratics and the local sandstone fragment in the iceberg deposit show conspicuous wear indicates that in the short distance such fragments traveled, and presumably under the thin, waning front of the glacier, there was nevertheless accomplished a very notable amount of erosion of these fragments, and it may be inferred that the bedrock surface over which the fragments were dragged was subjected to a like amount of reduction. This suggests that even the relatively thin and inactive frontal lobes of waning glaciers are quite effective erosive agents.

Summary.—Iceberg deposits of bowlders, found in fine-grained lake clay, occur in pockets, as if derived from single bergs. If that is the case the material brought by each berg is of considerable mass. The bowlders are in very high percentage of foreign, resistant rocks, and a very large proportion of the specimens shows signs of mechanical wear of glacial nature. Hence it is concluded that the iceberg deposits examined were from the bottom ice of the glacier. Locally derived material found in the deposits shows similar wear. Since these iceberg deposits must have been the very last deposits made by the last retreat of the ice, it is argued that the notable grinding of the local material indicates that even the thinned lobes of a waning glacier had considerable erosive effectiveness.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

LEITH, C. K. and MEAD, W. J. *Metamorphic Geology.* Henry Holt & Co., New York, 1915. Pp. xxiv+337, figs. 35, pls. 16.

This is one of the most valuable of recent petrologic textbooks. The experience of the authors in the interpretation of metamorphic processes would make this work of great value even though there were many books on the subject; since this is actually the only general textbook, it is doubly valuable and welcome.

Under the term rock-metamorphism the authors include not only the changes involved in the formation of rocks commonly called metamorphic, but also all mineralogical, chemical, and physical changes which have taken place in rocks subsequent to their primary crystallization from the magma, thus including in the definition cementation and rock-weathering. In other words, the metamorphic processes here included are both the destructive processes of katamorphism and the reconstructive processes of anamorphism, together forming the metamorphic cycle.

The writers take up first the katamorphism of acid igneous rocks, katamorphism being used "to cover all alterations of a disintegrating or decomposing nature, whether accomplished by weathering or by thermal solutions, whether at the surface or below." The most important phase of katamorphism is weathering, or the alteration of surface rocks by the agencies of the atmosphere and hydrosphere. By this process the rocks decompose and disintegrate, and part of the constituents are carried away in solution, while the residue forms a porous mass which in many cases retains the texture of the original rock. Clay, sand, carbonate, and salt in aqueous solution are the end-products of katamorphism. Chemically the changes are chiefly hydration, carbonation, oxidation, and desilication; mineralogically there is a destruction of some minerals and a simplification of others, the minerals in many cases passing through intermediate forms before reaching the simple end-products. Another change produced is one of volume, there being an increase by the formation of pore space, by the addition of water,

carbon dioxide, and oxygen, and by the decrease in the average specific gravity of the minerals formed.

The authors do not lay much stress upon the zones of katamorphism and anamorphism, emphasized by Van Hise, for the zone through which katamorphism extends, for example, has very indefinite limits, both katamorphic and anamorphic changes being possible simultaneously at moderate depths in different kinds of rocks, or in the same kind of rock under different conditions.

The weathering of granite is used as a type of katamorphism. The rock used as an example is a Georgia "granite," and although so called by Watson it is not a granite, neither mineralogically as shown by the table on page 6, nor chemically. It is a quartz-monzonite verging toward a granodiorite, and not greatly different from Lindgren's type granodiorite. So far as the results of the alteration go, however, it is immaterial what the rock is called, and the term granite may be used in the "commercial sense." In this chapter 16 pairs of analyses, representing the weathering of acid igneous rocks, are shown by "straight-line diagrams," which well illustrate the changes which have taken place.

The second chapter treats of the katamorphism of basic igneous rocks, 17 pairs of analyses being given in the second plate.

In the third chapter the production of bauxite and laterite by the extreme weathering of rocks is discussed, the authors maintaining that bauxite and the associated clays are the products of the surface weathering of syenite by normal processes of rock-decomposition, and that they are not chemical sediments. They believe that kaolin is an intermediate stage and that they can trace the gradation from syenite through kaolinized syenite to bauxite wherever fresh cross-sections appear. There is a good discussion of the formation of laterite and associated iron ores in Cuba.

A comparison of the two plates showing the hydrothermal katamorphism of 29 igneous rocks with the plates showing normal weathering gives a clear conception of the differences between these two types of alteration.

So far the book has dealt with the katamorphic destruction of igneous rocks and with the nature and distribution of the end-products. The katamorphism of sediments, ores, etc., is now taken up in several chapters, and is followed by 30 pages on the redistribution of the constituents of the average crystalline and igneous rocks during katamorphism. Here the redistribution of the constituents is considered in terms of sediments—first in weight proportions of shales, sandstones, and

carbonate rocks, then in terms of minerals, and finally in terms of chemical constituents.

For example, it is determined that the average analyses of shale, sandstone, and limestone should be combined in the proportions of 81.7, 12.05, and 6.25, or in round numbers 82, 12, and 6, to give an analysis as nearly as possible like that of the average igneous rock. If the average igneous rock is represented by some combination of granite and basalt, these being the most widespread types of igneous rocks, it should be possible, say the authors, to determine what proportions of granite and basalt will give an average that could be approximated by some combination of shale, sandstone, and limestone. For their granite and basalt analyses they use the average values computed by Daly. But this brings in a loose use of the terms granite and basalt, due to the fact that Daly's averages were computed from analyses of rocks which were not in every case actually granites and basalts but which had simply been given these names (in many cases certainly not in their modern sense) by the various geologists describing them. Instead of using these average analyses, it would have been much better if analyses only of rocks which are unquestionably granite and basalt had been used, even if they had been fewer in number. Thus the analysis on page 66, recomputed into the modal minerals (page 74), gives for granite a rock containing but 17 per cent of orthoclase while it carries 35 per cent of oligoclase ($Ab_{74}An_{26}$), besides biotite 6, muscovite 6, hornblende 2.5, quartz 31, magnetite 1.7, and ilmenite 0.3. The proportions of orthoclase to oligoclase are 17:35.5, making the rock a granodiorite, according to Lindgren's original definition, but just over the line from quartz-monzonite. (The orthoclase here forms 32.4 per cent of the total feldspar; Lindgren's division line is $33\frac{1}{3}$ per cent.) The basalt, also, has for its modal feldspar oligoclase ($Ab_{70}An_{30}$), and has 10.7 per cent orthoclase, besides augite 37, olivine 7.6, magnetite 5.8, ilmenite 0.73, and titanite 2.8. For a basalt the plagioclase is decidedly sodic, and the rock should rather be called a melanocratic orthoclase-bearing olivine-diorite. Comparing the modal minerals of these rocks with those in Clarke's average igneous rock, the authors found that the latter was too low in quartz, assuming that the normative quartz in 84 granites (Q=32.8) is the same as the modal. But normative quartz is almost invariably higher than modal. If analyses of true granites and true basalts were used instead of granodiorite and orthoclase-bearing olivine-diorite, the authors' and Clarke's averages would be more nearly alike. It is true that the modes given for these rocks were calculated from the

analyses, but the authors themselves say the computations represent "as nearly as possible the actual mineral composition of the rocks." Changing the granite (granodiorite) and basalt (diorite) analyses would probably give a different result for the average sediment, the proportions now found being 65 granite to 35 basalt.

Under the term anamorphism are included cementation, metasomatic replacement, rock-flowage, contact and thermal metamorphism, and the constructive changes which tend to make rocks coherent and crystalline. The anamorphism of clays through shale, slate, and schist to the contact phase, and of sands to sandstones and quartzites, and limestones to marble are all shown by numerous straight-line diagrams. Dolomitization is briefly touched upon.

In the fourth chapter of Part II, the dynamic and contact metamorphism of igneous rocks (rock-flowage) is treated. Changes produced in katamorphosed products of igneous rocks are clearly anamorphic, but igneous rocks do not necessarily pass through a katamorphosed state before becoming schists and gneisses. In such cases the katamorphic agents must in some way be simultaneously introduced. Alteration by hot water in the deeper zones is essentially anamorphic.

In the chapter on the textures and structures of dynamic metamorphism, rock-cleavage is regarded as the result of the orientation of mineral-grains or of the parallel arrangement of mineral-cleavages. The orientation of the mineral-grains is ascribed by the writers to differential pressures which caused the rock to flow. Recrystallization and the development of new minerals at right angles to the pressure and granulation and rotation of original minerals from random positions are also contributing factors in producing schistosity.

Secondary porphyritic textures, as shown by garnets, staurolite, andalusite, etc., are thought to have been caused by recrystallization, which took place after rock-flowage had ceased but while the rock was probably still under high pressures and temperature. The development of gneissic textures is considered, and Becke's and Grubenmann's views on the conditions of development of the crystalline schists are presented.

Part III treats of the determination of the origin of the metamorphic rocks. The first two parts of the book were devoted to the changes produced by metamorphism in sedimentary and igneous rocks. In this part the field and laboratory methods used in determining the origin of these rocks are discussed. Only four pages are devoted to the criteria of origin of sediments and residual rocks; a thorough treatment of this

part of the subject, say the authors, would involve the consideration of a wide range of conditions entering into sedimentation, such as is beyond the scope of the book. Twenty-two pages are devoted to primary gneisses and schists; the term primary gneisses being used for banded igneous rocks whose banding was produced during the consolidation of the rocks (ortho-gneisses, in part), and metamorphic gneisses for those that were formed by anamorphic processes (para-gneisses, in part). Among the criteria given for distinguishing primary from metamorphic gneisses are field relations, textures and structures, and mineral and chemical compositions. Instructive triangular diagrams are given showing the igneous or sedimentary characteristics of a rock.

A number of chapters are devoted to ocean, lake, river, and underground solutions as by-products of the metamorphic cycle; and there is a discussion of the metamorphic cycle as a basis for the genetic classification of commercial mineral products.

The last chapter of the third part deals with the net results of the metamorphic cycle, and the answer to the question, "Is the metamorphic cycle closed?" is that "adequate evidence of it is lacking . . . . such evidence as there is points rather toward the incompleteness of the cycle."

The fourth part, on laboratory work in metamorphism, is one of the most useful and instructive in the book. It treats of the megascopic and microscopic study of specimens and the measurement of specific gravity and porosity, a plate being given for calculating the porosity from the moisture of saturation and the specific gravity of the rock materials. It shows how analyses may be compared to determine the relative and absolute gains and losses of constituents, and gives instructions for the use of various straight-line and circular diagrams. There are instructions for comparing analyses by means of rectilinear coordinates, and for constructing triangular diagrams of various kinds. The determination of mineral compositions of rocks from their chemical analyses by recalculation or by the mineral slide-rule, and the calculation of volume- and energy-changes are treated, and finally there are suggestions for laboratory study.

The book is strongly recommended, not only to students of metamorphic geology, but to all students of petrology and to advanced students in economic or general geology. The authors are to be congratulated on having presented the subject in a clear, simple, and, at the same time, most interesting way.

LEISS, C., and SCHNEIDERHÖHN, H. *Apparate und Arbeitsmethoden zur mikroskopischen Untersuchung kristallisierter Körper.* Handbuch der mikroskopischen Technik, Part X, pp. 94, figs. 115.

A manual giving in simple form the more important apparatus and methods for the microscopical determination of crystals. The authors say in the preface that the book is intended only for the use of amateurs, teachers, and collectors of minerals who wish to make use of the polarizing microscope. It is, however, a book that can be read with profit by the average student of petrology. The authors not only deal with the polarizing microscope, but describe the preparation of thin sections, the use of the axial angle apparatus, refractometer, etc. The theoretical discussion is simply presented and good, and embraces all the essentials.

MEAD, W. J. "Occurrence and Origin of the Bauxite Deposits of Arkansas," *Econ. Geol.*, X (1915), 28–54, pls. 5, figs. 7.

The writer believes that the bauxite of Arkansas is derived from the weathering of the underlying syenite, and gives analyses showing the transition. Previous writers maintained that the deposits were chemical sediments or due to the action of hot springs from the still heated syenite.

MENNELL, F. P. *A Manual of Petrology.* Chapman and Hall, London, 1913. Pp. iv+256, figs. 122.

This little book is an enlargement of Mennell's *Introduction to Petrology*, which was published in 1909. The book has been practically rewritten, new cuts have been added, and the form has been considerably changed. Fifteen pages are devoted to the general properties of minerals, 11 to optical methods of determination, 53 to the rock-forming minerals, 38 to general petrology, 56 to the igneous rocks, 12 to the sediments, 32 to metamorphism, 7 to weathering, 10 to the distribution of the chemical elements, 9 to radio-activity, and 7 to the collection and preparation of material.

MERWIN, H. E. "Measurement of the Extraordinary Refractive Index of a Uniaxial Crystal by Observations in Convergent Light on a Plate Normal to the Optic Axis," *Jour. Washington Acad. Sci.*, IV (1914), 530–34.

MILLER, WILLET G., and KNIGHT, CYRIL W. *The Pre-Cambrian Geology of Southeastern Ontario.* Report Bureau Mines, XXII, Part II, Toronto, 1914. Pp. vi+151, figs. 67, pls. 4, maps 7, bibliographies.

The oldest rocks of the region are essentially green schists of igneous origin, which were extruded during the Keewatin period. In other parts of Ontario this was a period of great volcanic activity, and enormous quantities of rock were erupted. Succeeding this active period came one of sedimentation during which the Grenville series, variously estimated at from 50,000 to 94,406 feet in thickness, and consisting of crystalline limestone, greywacke, quartzite, and slate and iron formations, was laid down. During Laurentian times both the Keewatin and Grenville rocks were invaded by great masses of granite and syenite. This caused a folding and crumpling of the older rocks, and their alteration to schists and gneisses. Injection schists appear in certain places. Later, erosion removed much of the Keewatin and Grenville material and exposed the deep-lying igneous rocks. The region now became partially or entirely submerged and beds of conglomerate and quartzite of the Hastings series were deposited. The youngest pre-Cambrian rocks are post-Hastings, and include granite, diabase, and basalt. During the Paleozoic the surface sank below sea-level, and limestones, sandstones, and shale were deposited, and these were later elevated to their present position.

Numerous analyses are given, but little attempt has been made to describe the rocks petrographically.

Reviews

Geologic Atlas of the United States: Leavenworth-Smithville Folio, Kansas-Missouri. By Henry Hinds and F. C. Greene. U.S. Geological Survey Geol. Folio No. 206. Pp. 12, maps, ills. Washington, D.C., 1917.

This folio covers a part of northeastern Kansas and northwestern Missouri, and is traversed by the Missouri River. The rocks exposed are all Pennsylvanian, but embrace four formations—Kansas City, Lansing, Douglas, and Shawnee—in order of age from older to younger. The lower two are largely limestone, the third largely shale, and the fourth chiefly shale, capped by sandstone. They show very little tilting or disturbance. The Douglas formation includes thin and unimportant beds of coal. Borings have penetrated coal beds of greater thickness (up to 36 inches) in formations not exposed. These are found at various levels from 600 to 1,200 feet depth. Five coal mines have an annual production of 300,000 tons of hard bituminous coal. The limestone formations include much rock suitable to yield a "good grade of high calcium lime."

These quadrangles fall just inside the limits of Kansan glaciation. The post-Kansan erosion, however, has been so great that the glacial deposits are reduced to narrow strips along the divides, and small patches on the valley slopes. The thickness of the drift where it is best preserved on the main divides is nearly 100 feet, and it is not unlikely that there was originally about that thickness over the whole surface. In that case erosion has removed nearly 90 per cent of the glacial formation. There has also been some rock erosion by the Missouri and its tributaries in post-Kansan time, but in the reviewer's opinion much less than is set forth in this folio.

It has long been known that the Missouri River is made up of streams which were thrown into this drainage basin by glaciation in the Dakotas. The Missouri is thus using in this part of its course the valley of a small stream, smaller perhaps than Kansas River, which it joined at the site of Kansas City. The convergence of drainage in the quadrangles covered by this folio is toward the south part of the Leavenworth quadrangle, nearly down to the junction with Kansas River. The main streams seem also to be following courses that had been established long

before the Kansan stage of glaciation. The topographic maps seem to give no warrant for the view expressed in this folio that Missouri River was thrown across a col to connect with Kansas River at a time not earlier than the Kansan stage. Certain gravel deposits found at Weston, Missouri, and at widely separated intervals farther east are interpreted in this folio to be the product of a small stream flowing eastward from the present line of the Missouri at Weston, during the Aftonian stage of deglaciation, and a sketch map (Fig. 8) is introduced to illustrate this conception. The reviewer noted when in field conference with the junior author in 1913, and it will also be seen by descriptions given in the text, that insufficient evidence has been obtained to establish any stream connection between these widely separated exposures of gravelly material. It seems remarkable, therefore, that such a fundamental interpretation as that of the shifting of the course of one of the largest streams on the continent is here suggested. In the reviewer's opinion these gravel beds were deposited in places where water chanced to be issuing from the border of the melting Kansan ice sheet, in some cases at levels considerably above those of the neighboring valley bottoms. In exposures on the Kansas City and St. Joseph electric line south of Platte River, which are included in the supposed stream deposits, the beds dip southward directly away from the valley. In these exposures there is only a gummy, slightly pebbly clay above the gravel, such as Shimek has referred to water action and named Loveland formation. Hence it is not certain that these particular gravel deposits were overridden by the Kansan ice.

There is a reddish silt deposit covering part of the Kansan till on the upland which is referred in this folio to the Loveland formation, and, following Shimek, is classed as a water deposit. So far as the reviewer has had opportunity to study this reddish silt in Iowa and northwestern Missouri he has failed to see any clear evidence that it was laid down in water. It is a very different deposit from the gummy, pebbly clay that overlies the gravel deposits above noted, being looser textured and free from pebbles. It may prove to be a loess of greater age than the widespread, commonly recognized loess of that region. The reddening seems likely to have been produced by deep oxidation in the warm interglacial stage between the Kansan and Illinoian stages of glaciation. The loess above it is mainly of brown color, but includes layers and lenses of bluish loess in its lower part. This loess was not laid down until the Kansan drift had been greatly eroded, and is probably of similar age to the loess of eastern Iowa and western Illinois, which covers the black soil (Sangamon) formed on the Illinoian till sheet.

FRANK LEVERETT

The Geology of the Lake District and the Scenery as Influenced by Geological Structure. By J. E. MARR. Cambridge: Cambridge University Press, 1916. Pp. 220, figs. 51, map in pocket.

The English Lake District is well adapted to call forth the interest of the geological student by reason of the variety of its geological structure and the significance of its physical features. As an increasing number of those interested in geology visit it each year, and the need of a special treatise upon its geologic features has come to be felt, the author has prepared a condensed account of the geology of this picturesque area.

The Lake District proper is composed of Lower Paleozoic strata, but its borders are formed of a roughly annular girdle of newer strata, partly of Carboniferous age, but partly belonging to the Permian and Triassic. The Lower Paleozoic rocks were profoundly affected by the great Caledonian orogenic disturbance at the close of the Silurian. Great overthrusts of the Scottish Highland type appear to have developed here also, though the author considers "lag fault" as an alternative hypothesis in the explanation of the observed phenomena.

The last third of the book describes and discusses the critical features of the Pleistocene ice sheet, which, by its erosive and depositional work, has contributed so much to the beauty and interest of this celebrated region.

R. T. C.

Origin of the Iron Ores at Kiruna. By REGINALD A. DALY. Vetenskapliga och praktiska Undersökningar. Lappland. Anordnade af Loussavaara—Kürunavaara Aktiebolag. Geology No. 5. Stockholm, 1915. Pp. 1–30, figs. 4.

Professor Daly, thoroughly familiar with the writings of Geijer, Stutzer, and others, has made a short field study of the Kiruna district, particularly of the nature and origin of the numerous small inclusions of iron ore scattered through the quartz porphyry which forms the hanging wall of the ore bodies. These are commonly held to be xenolithic inclusions derived from an older invisible ore body, but the writer concludes, as a result of his field study, that the ore inclusions represent so many frozen-in units of differentiation modified in part by later resorption. The ore bodies are believed to have formed by the gravitative assemblage of similar units at the base of the quartz porphyry. Geijer has emphasized the view that both the iron ores and quartz porphyry are of extrusive origin. Professor Daly, following Stutzer,

holds that the quartz porphyry and the underlying syenite are essentially contemporaneous parts of a composite laccolith. It is suggested that the heated condition of the syenite at the time of the quartz-porphyry intrusion favored notable differentiation by prolonging the magmatic life of the later intrusive.

The origin of the ore inclusions in the porphyry is the crucial point in any hypothesis of the origin of the Kiruna ores. Professor Daly's view is a satisfactory interpretation of the field relations; likewise it accords best with recent opinion concerning differentiation processes.

H. R. B.

Journal of the Washington Academy of Sciences, V, 1915, 687 pages.

Articles of geologic interest in recent numbers of the *Journal* are: "The Paleozoic Section of the Ray Quadrangle, Ariz.," by F. L. Ransome; "Factors in the Movement of the Strand Line," by Joseph Barrell; "The Calculation of the Calcium Orthosilicate in the Norm of Igneous Rocks," by H. S. Washington; and "The Solubility of Calcite in Water in Contact with the Atmosphere, and Its Variation with Temperature," by R. C. Wells. Chase Palmer contributes an article on "Bornite as Silver Precipitant."

H. R. B.

Mineral Land Classification in Part of Northwestern Wisconsin. By W. O. Hotchkiss, assisted by E. F. Bean and O. W. Wheelwright. Wisconsin Geol. and Nat. Hist. Survey, Bull. No. 44, 1915. Pp. 376, pls. 8, figs. 39, maps 90.

This volume constitutes the report on the land classification of 87 townships in northern Wisconsin. The work was done during the field seasons of 1913 and 1914. The object of the survey was "to discover the evidence that exists as to the presence or absence of iron-bearing rocks, and as to the geologic structure of the region." The difficulties encountered either by the geologist who attempts to unravel the pre-Cambrian geology of this heavily drift-covered area, or by those who seek to locate iron ores here may be appreciated from the fact that in this area of over 2,000,000 acres the total exposed area of rocks of all kinds does not exceed 300 acres. Naturally, the report is based largely on the comprehensive series of magnetic observations.

Part I includes chapters treating of the methods of field work, general geology of the area covered, magnetic observations, land classi-

fication, and methods of exploration for iron ore. Chapter iv, on magnetic observations, gives a rather full explanation of the instruments used, the interpretation of observations made with them, and their capabilities and limitations.

Part II consists of the detailed township maps and the accompanying descriptions. Each township is fully described under the following heads: surface features, glacial drift, general geology, magnetic observations, land classification, and recommendations for exploration.

H. R. B.

Coal Resources of District VIII (Danville), Illinois. By F. H. KAY and K. D. WHITE. Ill. State Geol. Survey, Coal Mining Investigations, Bull. No. 14, 1915. Pp. 68, pls. 7, figs. 10.

The geology of a part of this district has been described by M. R. Campbell in the Danville Folio of the U.S. Geological Survey. The present bulletin treats chiefly of the coal resources. The principal coals are in the upper Carbondale and lower McLeansboro formations. Lenticular masses of shale locally called "rolls" are common within the coal beds. Their present shape is the result of depositions in small basins and the subsequent settling of the somewhat plastic incompressible clay into the highly compressible vegetal mass. More than 58,000,000 tons of coal have been mined in this district since 1880; 1,494,000,000 tons remain in the ground.

H. R. B.

Newly Discovered Beds of Extinct Lakes in Southern and Western Illinois and Adjacent States. By E. W. SHAW. Ill. Geol. Survey, Bull. 20, 1915. Pp. 141–57.

During some parts of Pleistocene times aggradation by the Ohio and Mississippi rivers exceeded that of certain of their tributaries—those which received little glacial drainage. The valley fillings of the master-streams therefore dammed these tributaries, and lakes formed in their lower courses. The deposits that were laid down in these ponded waters are about 100 feet thick at the mouths of the tributaries and thin out upstream. The Big Muddy River is a typical case.

Shore features are poorly developed except along the Pond River near Madisonville, Ky., 50 miles from the Ohio River. The lakes were relatively short-lived, and their levels were subject to considerable fluctuations, owing to the great range of high and low water of the major streams.

There were two periods of lake development. During the intervening epoch the first deposit was almost cut through. The two stages of filling are now marked by terraces, the later of the two being 10 feet to 20 feet lower than the first.

The older of the two stages is younger than the Illinois till—probably of late Illinoian age. The other is "in or near Wisconsin time."

H. R. B.

The Ellamar District, Alaska. By S. R. CAPPS and B. L. JOHNSON. U.S. Geol. Survey, Bull. No. 605, 1915. Pp. 125, pls. 10, figs. 10.

Previous writers have considered that the copper deposits of the Prince William Sound region are genetically related to basic lavas, being formed either as concentrations of disseminated copper minerals of these greenstones or in connection with basic intrusives. The deposits are in shear zones along fault planes, principally in the greenstones. The ores carry, besides copper, some gold and silver. The minerals are chiefly sulphides, chalcopyrite, pyrrhotite, and pyrite predominating, with smaller amounts of sphalerite, galena, and arsenopyrite. The ore minerals cement or replace the shattered country rock. Quartz-filled fissures carrying similar minerals are less common. The evidence obtained indicates that the deposits were formed by primary sulphide impregnation along the fracture zones by rising magmatic solutions. Both the gold and copper veins of this region are believed to have been formed during a single period of mineralization closely following and genetically related to the late Mesozoic granitic intrusives.

H. R. B.

Mineralogy, Crystallography and Blowpipe Analysis, 5th edition. By MOSES and PARSONS. New York: Van Nostrand & Co. (1916). Pp. xiii+631, figs. 575.

The new edition has been expanded by the addition of new economic groups, by the discussion of origin and association of minerals, by added discussion of crystal optics, and by new determinative tables. The economic basis for classification is retained and emphasized, though many minerals of no economic importance are included. Perhaps the greatest difficulty arising from this classification is in the breaking up of customary crystallographic groups. For example, the rhombohedral carbonates must be sought out by looking through the calcium, mag-

nesium, iron, manganese, and zinc groups. The greatest need for improvement in the earlier editions was in the scope of the determinative tables, which have been expanded with considerable success.

A. D. B.

Microscopical Determination of the Opaque Numerals. By JOSEPH MURDOCH. Pp. vi+165, figs. 9 (index of cuts).

A determinative key for use in connection with the metallographic microscope is provided in this book. As the first work of its kind the book has already found wide use. The fundamental basis of classification is color (of the polished surface), followed by hardness and microchemical tests. A number of so-called minerals are thought by the author to represent mixtures rather than well-defined compounds, but these, with a number of unknown minerals discovered in connection with the studies on which the key is based, are given place in the key.

The book is remarkably satisfactory for a first attempt in the field, and has already made possible the use of the metallographic microscope in colleges where no research work can be undertaken.

A. D. B.

Geologic Map of West Virginia. By I. C. WHITE, R. V. HENNEN, D. B. REGER, and R. C. TUCKER. Morgantown, W.Va.: State Geological Survey, 1917.

A revised map of the state, showing coal, oil, gas, iron ore, and limestone areas, on the scale of eight miles to the inch. A list of coal mines by counties, printed on the sheet, includes those in operation up to July, 1917, except for some that are doubtless only temporary producers. The geology of areas other than those mentioned is not shown, nor is there any stratigraphic division of the limestone areas.

A. D. B.

Economic Geology, 4th edition. By HEINRICH RIES. London: Wiley & Sons, 1916. Pp. xviii+856, figs. 291, pls. LXXV.

In the fourth edition this well-known work has been considerably expanded and materially improved, both in the treatment of topics and in the descriptions of deposits. Many illuminating figures and diagrams have been added. Among the more noteworthy changes are the expansion of the chapter on petroleum and the chapter on ore deposits, and the addition of descriptions of many of the important Canadian deposits.

As with former editions, the reviewer feels a little lack of coherence between chapters—a difficulty that is perhaps insurmountable in a text of this sort.

A. D. B.

Investigation of the Peat Bogs and Peat Industry of Canada, 1911–12. By A. V. ANREP. Department of Mines, Canada, Bull. No. 9. 1914.

A detailed report of preliminary investigation of peat bogs in the provinces of Quebec and Ontario.

Coal Fields and Coal Resources of Canada. By D. B. DOWLING. Department of Mines, Canada. Memoir 59, 1915. Pp. 174, maps 7, figs. 9.

Chiefly material reprinted from "Coal Resources of the World" compiled for the Twelfth International Geological Congress.

Coal Fields of British Columbia. By D. B. DOWLING. Department of Mines, Canada, Memoir 69, 1915. Map 1, diagrams 23. Pp. 350.

Discusses the coals of the Cretaceous and Tertiary horizons in various areas of British Columbia.

E. A. S.

British and Foreign Marbles and Other Ornamental Stones. By JOHN WATSON. Cambridge: Cambridge University Press. New York: Putnam, 1916. Pp. 485. $1.50.

In addition to marble, numerous other ornamental stones are discussed, the most important being onyx marble, malachite, alabaster, fluorspar, quartzite, labradorite, lapis lazuli, serpentine, steatite, and jade. Includes brief description of the occurrences.

E. A. S.